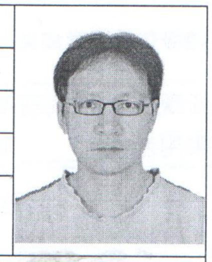
专业技术职务申报简表（理工类-2016版）

所在单位：北京航空航天大学生物与医学工程学院　　　　填表时间：2016年5月20日

姓名	丁立	性别	男	出生年月	1971.3	
最后学历	研究生	学位	博士	拟申请专业技术职务	教授	
现任专业技术职务	副教授			现任专业技术职务批准时间	2002.9	
申报学科（一级/二级学科名称）		生物医学工程		研究方向	人体工效学	
申报类别	☑教师 □科学研究 □工程 □实验 □其他					

主要学习工作简历及海外经历（从高中起，应连续）

起止年月		学习与工作单位	学历、学位、专业、职务	
起	止			
1985.9	1988.7	永善县一中		高中
1988.9	1992.7	哈尔滨船舶工程学院	热能工程	本科
1992.8	1995.8	天津新河船厂动力处		助理工程师
1995.9	1997.7	哈尔滨工业大学	工程热物理	硕士
1997.9	2000.9	北京航空航天大学	人机环境工程	博士
2000.9	2004.8	昆明理工大学交通学院	交通工程	副教授
2002.9	2004.12	北京航空航天大学	力学	博士后
2011.5	2012.5	康奈尔大学（365天）	人类生态学院	访问学者
2004.10	至今	北京航空航天大学	生物医学工程	副教授

研究水平和特点概述（限填200字）	任现职以来，面向国家重大需求开展航天员脑—手系统作业能力、航天服热控、飞行员个体防护装备相关基础和关键技术研究，研究成果已在“飞天”服和4代机装备型号和科研方面应用。主持国家自然基金、国家支撑计划等项目10余项目，经费800余万元。以第一、通讯作者等在本领域重要国际学术期刊和会议发表论文40篇（8篇SCI，22篇EI），授权专利5项、国家标准1项；主持1门精品课，编著1部工信部“十二五”规划教材。

请填写任现职以来取得的代表性学术成果情况（限填5项，其中论文不少于3篇，奖励、专著或教材等各不多于1项）

学术论文题目	发表刊物或会议	发表（出版）时间	收录、他引情况	影响因子	期刊分区及排名/总数	作者排名
Effects of EVA gloves on grip strength and fatigue under low temperature and low pressure	Applied Ergonomics	2016.03	SCI/0次	2.203	Q1，2/15，(工效学)	通讯作者
Muscle weakness is related to slip-initiated falls among community-dwelling older adults	Journal of Biomechanics	2016.01	SCI/0次	2.751	Q2，23/76 (生物医学工程)	第一作者
Optimizing the physical ergonomics indices for the use of partial pressure suits	Applied Ergonomics	2015.03	SCI/0次	2.203	Q1，2/15，(工效学)	第一作者
An experimental study on the ergonomics indices of partial pressure suits	Applied Ergonomics	2013.05	SCI/0次	2.203	Q1，2/15，(工效学)	通讯作者
Study on functional relationships between ergonomics indexes of manual performance	Acta Astronautica	2008.10	SCI/2次	1.211	Q1，5/30，(工程,航空)	2(指导老师)

任现职以来发表论文及收录情况：收录类别、作者贡献（第一、通讯等）仅计算1次；论文收录以图书馆检索证明为准，未检索到的来源刊论文仅计算1篇

类别	合计	SCI	SSCI	CSSCI	EI	ISTP	中文核心期刊	其他
一、符合职称申报条件论文	42	7	1		22		10	2
其中：1.第一作者	16	3			8		5	
2.学生第一本人第二作者	5	1			4			
3.通讯作者	19	3	1		10		5	
二、其他	2							国防报告

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获奖项目	奖励名称	颁奖部门	奖励级别	获奖时间	人数	排名
北航科技进步二等奖	EVA 手套热特性测试装置研制	北京航空航天大学	校级	2009	10	1
“成飞”奖教金二等奖	“成飞”奖教金	北京航空航天大学	校级	2010	1	1
校级优秀教学成果二等奖	开放式创新性“生物（医学）工程专业综合实验”课程的教学改革与实践	北京航空航天大学	校级	2009	5	3

任现职以来共获得排名第一（含学生第一本人第二）授权专利 5 项，其中发明专利 5 项，实用新型 ____ 项，外观设计 ____ 项。请填写任现职以来共获得已授权专利情况（限填 3 项）

专利名称	专利类型	授权日期	批准机构	专利号	权利单位	人数	排名
低压防护手套灵活性测试装置	发明专利	2014.12	国家知识产权局	ZL 2012 1 0570139.0	北京航空航天大学	7	1
超低温恒温抓握棒装置	发明专利	2013.04	国家知识产权局	ZL 2010 1 0184103.X	北京航空航天大学	2	1
低温有压手套作业能力测试装置	发明专利	2012.12	国家知识产权局	ZL 2009 1 0244608.8	北京航空航天大学	2	1

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项目名称	项目来源	起止时间	到款/经费总额
显控界面工效学仿真测评技术和标准研究	国家科技支撑计划	2014.1-2016.12	356/356
基于人—手套系统的舱外服手套工效研究	国家自然科学基金委	2012.1-2015.12	58/58
舱外航天服手套的热防护研究	国家自然科学基金委	2005.1-2007.12	22/22
城市公共交通设施工效学设计指南	国家标准委	2013.1-2014.12	7.5/7.5
防冰系统实验技术研究与验证	ATPD 项目	2008.1-2010.12	36.4/90

任现职以来其他项目情况（限填 3 项）

项目名称	项目来源	起止时间	负责人	承担份额/总额	主持/参与
船舶使用与维修多人协作任务仿真与评价技术研究	舰船重工七〇一	2013.1-2014.11	丁立	45/45	主持
舱外手套力学特性仿真分析及***手套试验台	航天员科研训练中心	2013.1-2014.11	丁立	70/70	主持
手套热特性测试装置研制	航天员科研训练中心	2006.10-2008.10	丁立	36/36	主持

任现职以来的教育教学情况：主讲课程共计 1188 学时；指导本科生毕设 25 人次；指导硕士研究生 18 人次；指导博士研究生 3 人次。请填写任现职以来主讲的 3 门课程

课程名称	起止时间	课程学时	本人授课学时	授课次数	授课对象	课程性质
人体工效学	2005.9-至今	48	40	11	本科生	必修课
连续介质力学	2005.3-2011.5	68	34	8	本科生	必修课
人体工效学及康复工程	2006.3-至今	48	40	10	硕士生	学位课

主要学术兼职（限填 3 项）

学术兼职名称	受聘日期	颁授机构
青年委员	2013.11	中国航空学会人机与环境工程专业委员会
基础研究基金专家	2012.12~2016.12	中国航天员科研训练中心人因工程国防科技重点实验室

任现职以来其他业绩成果（限 100 字）	（1）成果用于“神七”和“4 代机”等研制，有“总装司令部”和“921”等出具的 9 个应用证明。 （2）发布 1 项国家标准。 （3）完成 1 门校级精品课，编著 1 本工信部“十二五”教材，指导学生获“冯如杯”二等奖 4 次。

本人确认表内所填内容属实，如与事实不符，本人愿承担一切责任。 本人签字：丁立 日期：2015.6.1

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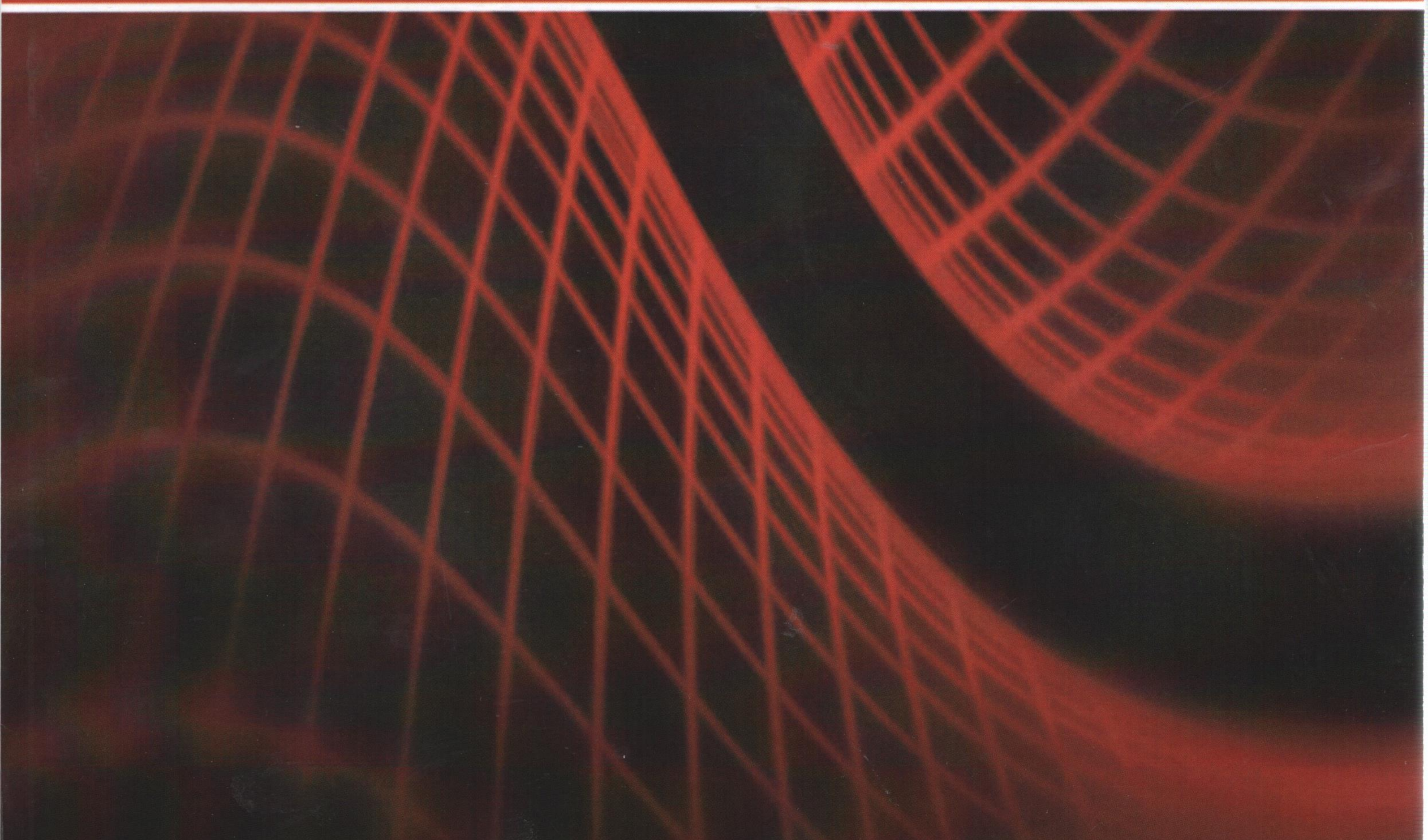
HUMAN FACTORS IN TECHNOLOGY AND SOCIETY



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Effects of EVA gloves on grip strength and fatigue under low temperature and low pressure

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ABSTRACT

Objective: To study the effects of wearing extravehicular activity (EVA) gloves on grip strength and fatigue in low temperature, low pressure and mixing of two factors (low temperature and low pressure).
Methods: The maximum grip strength and fatigue tests were performed with 10 healthy male subjects wearing gloves in a variety of simulated environments. The data was analysed using the normalization method.
Results: The results showed that wearing gloves significantly affected the maximum grip strength and fatigue. Pressure (29.6, 39.2 kPa) had more influence on the maximum grip compared with control group while low temperatures (−50, −90, −110 °C) had no influence on grip but affected fatigue dramatically. The results also showed that the maximum grip strength and fatigue were influenced significantly in a compound environment.
Conclusions: Space environment remarkably reduced strength and endurance of the astronauts. However, the effects brought by the compound environment cannot be understood as the superimposition of low temperature and pressure effects.

1. Introduction

Strength is the source of manual performance, and under the control of the brain it can realise precise manual performance by contraction force from the upper body and muscles of various hands parts. Up to 90% of actions in extravehicular activity (EVA) are performed by the upper body (Zhang et al., 2011). However, astronaut operation strength during extravehicular activity decreased dramatically due to the combined effect of glove pressure, low temperature and glove structure (Ding et al., 2005). Therefore, in the development process of EVA gloves, the major problem is how to maintain necessary strength during extravehicular activity. Endurance and strength are always considered together in the experiments because enough physical strength is the premise to complete the work. A reduction in strength and fatigue will lead to additional energy expenditure and fatigue, and a result could be a serious accident.

Scholars have studied various elements affecting hand strength from different perspectives. Geng researched the influence of low temperature on performance from aspects of subjective feelings and finger temperature measurements when in touch with low-temperature objects (Geng et al., 2001); Aldien illustrated the pressure distribution of the hand-handle operation interface by studying hand forces and handle size (Aldien et al., 2005). As far as the study of an EVA glove is concerned, Buhman showed the influence of the glove on maximum grip strength from glove structure, pressure, load, handle structure (Buhman et al., 2000). However, they only conducted single-factor analysis of each element, and the influence of low temperatures was not included. Tsaousidis studied the effects of gloves on maximum force and the rate of force development in pinch, wrist flexion and grip (Tsaousidis and Freivalds, 1998). By low-pressure chamber experiments, Bishu established the maximum limits of strength and fatigue when performing all kinds of tasks with gloves, which was manifest in the relationship between strength and fatigue (Bishu et al., 1995). Francisco studied the relationship between strength and dexterity by dynamic pinch performance (Valero-Cuevas et al., 2003). However, these studies mainly focused on single-factor effects on strength. There has been no definite conclusion on the

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interaction (addition, subtraction or combination) of glove pressure, low temperature and glove structure on strength, which is the real condition of EVA.

Therefore, this article studies hand strength under the combined influence of glove strength and low temperature and takes maximum grip strength and grip fatigue as essential evaluating indicators.

2. Methodology

2.1. Subjects

Ten male volunteers from university joined this experiment. The length of their hands was 18 ± 0.3 cm. The width of hands was 10.5 ± 0.2 cm. They were all right-handed and volunteered to participate in the experiment.

2.2. EVA glove

We used a replica of an EVA glove from the Astronaut Centre of China to conduct the tests. It had two parts: pressure glove and TMG. During the EVA, it was a part of the spacesuit. The pressure inside the clothing was constant. The pressure between the inside and outside of the glove was 29.6 (US)/39.2 (Russia) kPa. The test on the ground could simulate pressure differential only because of gravity. However, the state of the glove was similar. For specific content, refer to section 2.5 and Fig. 1.

2.3. Experimental settings design

The experiment included three variables: pressure, ambient temperature (AT), and grip bar surface temperature. Therefore, the experiment had five groups (Table 1). The first one was the control group, where the environment and grip bar temperature were 25 °C, and pressure was 0. This group was mainly used for comparison with other data. Group I simulated different pressures (22.1/29.6/39.2 kPa) (Ding et al., 2005), but the other variables were the same. These pressures were standard stamping data for EVA gloves. The variables in Group II were the same as the control group, except the grip bar surface temperature (−50/−90/−110/−130 °C). We designed this group because grasping low temperature objects was a common action in EVA activities. According to the literature, the surface temperature of objects in space is between −50 and −130 °C (Zhang et al., 2011). Group III simulated a compound environment in which the pressure and the temperature changed. The pressure was 39.2 kPa, grip bar surface temperature was −50/−110/−130 °C, and the other variable was the same as the control group. We determined this pressure because this study mainly focused on the Chinese EVA glove. In Group II, we found that there was no significant difference between −50 and −90 °C, so we ignored −90 °C in Group III. In order to simulate an environment closer to the real EVA, we designed Group IV to compare with the Group III data. In Group IV, the EVA gloves would be put in a −50 °C environment. The pressure was 39.2 kPa, and the grip bar temperature was −50 °C. At this point, heat loss occurred at both the palm side and back side of the glove, and the surface temperature of the hand fell even faster.

Table 1
Study design under different pressure and temperature.

No.	Pressure (kPa)	AT (°C)	Grip bar temperature (°C)
Control group	0	25	25
I	22.1/29.6/39.2	25	25
II	0	25	−50/−90/−110/−130
III	39.2	25	−50/−110/−130
IV	39.2	−50	−50

All the tests were performed when subject was wearing gloves.

2.4. Measurement

2.4.1. Strength

According to the ways of force imposed by hands in manual work, hand strength can be divided into grip, pinch and twist. Grip strength is caused by bending all the fingers together except the thumb. Pinch results from squeezing between fingertips. Different from grip and pinch, a twist completes work by the resulting moment and is relevant to the friction coefficient of the object surface. This article chose maximum grip strength as the object of study because strength studies of EVA gloves were often based on hand-handle interface with grip strength as the main method. Moreover, according to Chen's research (Chen et al., 2006), a correlation did exist among grip, pinch and twist, thus grip could be used in tests in place of the other two forces.

2.4.2. Grip fatigue

Muscle fatigue may occur after long-time exertion of force, and in turn it will affect normal operation. Fatigue has a direct relationship with operation strength and time, namely work power.

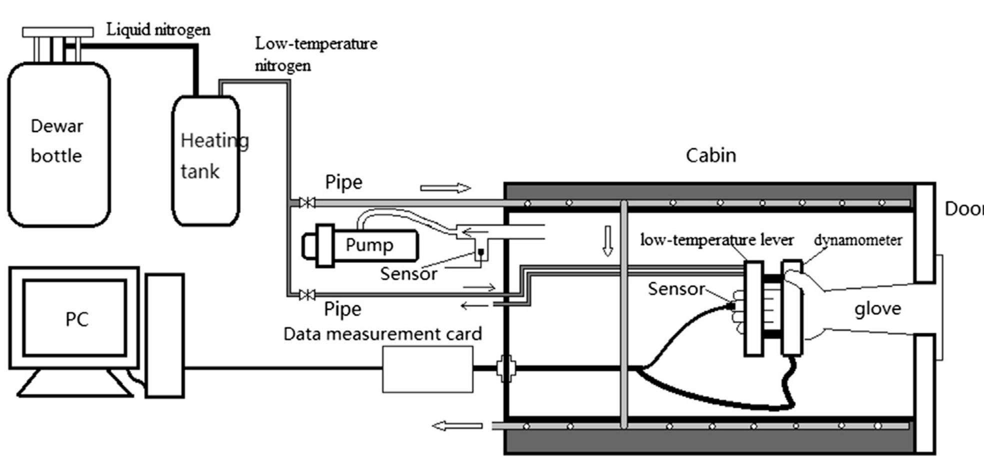


Fig. 1. Low-temperature simulation cabin and measurement equipment.

Because a comparatively large number of muscles is involved in gripping, fatigue appears more quickly and obviously, especially in extravehicular activities (Ding et al., 2009). That is why grip strength was chosen in the fatigue test. On the basis of the previous studies in this laboratory, dynamic grip and static grip were combined in this experiment.

2.5. Equipment

Experiments were conducted in a low-temperature simulation cabin designed for EVA gloves (Fig. 1), which was composed of a grip measurement system, temperature measurement system, refrigerating (cooling) system and pressure system.

The grip acquisition system includes low-temperature dynamometer, data measurement card (Kangsente, XST/A-H1MT0B3S1N) and self-developed grip acquisition system based on a monitor and control generated system (MCGS). Its functions include acquiring, real-time displaying and recording grip strength values. The dynamometer was composed of measurement lever and low-temperature lever. The former was an elastomer fixed with pressure sensors, and the grip strength was converted by the elastic deformation and measured by sensors. The latter was a hollow metal circular cylinder. Liquid nitrogen could be injected from one end to make the temperature reach the ideal value in the experiment. When using the dynamometer, subjects touched the surface of the low-temperature lever with their fingers and pressed the dynamometer with their palms to generate grip strength data. The working theories behind grip measurement system were that when the dynamometer is grasped, pressure signals are received by pressure sensors and transformed into voltage signals, then acquired through data measurement card and stored in the Excel worksheets by running the MCGS grip measurement system. The test precision was 0.1 kg.

The temperature measurement system included a resistance temperature sensor (PT-100), digital meter and temperature data measurement system based on Kingview platform. The system was designed to collect, real-time monitor and record the temperature change of dynamometer surface, environment and fingers. The principle of operation was that temperature signals from various temperature-measuring points were transformed into resistance values by temperature sensors, and then transmitted to a digital meter, which could transform those values into digital signals. The test precision was 0.1 °C.

The cooling system was composed of a Dewar bottle, heat installation, cabin and low-temperature dynamometer. It was designed to reach various low temperatures required by dynamometer or low-temperature cabin. The way of controlling the temperature was to let liquid nitrogen flow out of the Dewar bottle and flowed into heat installation, inside which it gasified into low-temperature nitrogen. The low-temperature nitrogen finally flowed into the dynamometer and low-temperature cabin. The principle is similar to a radiator. The temperature of the dynamometer was controlled by adjusting the volume of gasified nitrogen through a valve, while the temperature in low-temperature cabin was controlled by the volume of liquid nitrogen flow directly. Temperature precision of the dynamometer was 2 °C, and test cabin was 1 °C.

The pressure system included a vacuum pump, vacuum gauge, low-temperature cabin and simulated EVA glove. The system was designed to achieve pressure difference between inside and outside of the gloves by drawing off air in a low-temperature cabin using a vacuum pump. The operational principle of this system was that the low-temperature cabin was a sealed hollow metal cylinder when the door of the cabin was closed. The glove was fixed on the cabin door, with the external surface contacting the environment in the low-temperature cabin, and the interior surface was exposed to the atmosphere. Drawing off air in the low-temperature cabin with the vacuum pump, pressure was monitored by a vacuum gauge. The interior of the glove was connected with the outside atmosphere, so the pressure difference was the difference between atmospheric pressure and pressure inside the cabin. When astronauts performed with pressured EVA costumes in space, the environment was considered as a vacuum, and the pressure difference was the air pressure of costumes. The relative pressures of gloves under the above two circumstances could be regarded as the same. Pressure-controlling precision was 10 Pa.

2.6. Procedures

Before the experiment, a low-temperature cabin was cooled and the air was drawn off to make cabin and gloves meet the designing demands of the test group. Subjects were asked to put their hand into the glove with temperature sensors attached inside to conduct a grasping test. When performing experiments, the subjects were seated on a bench with appropriate height, thus avoiding the influences of push or pull brought by the centre of mass moving forward or backward. The position of the dynamometer could be adjusted by preference of the subjects to help them exert maximum grip strength. The procedures were as follows:

(1) Grip strength. Subjects were asked to grip the dynamometer using their maximum strength for three times every 3 min. Then the averaged value was taken as the subjects' maximum grip strength (F_{max}).
(2) Grip fatigue. Subjects grasped the dynamometer uniformly with the frequency of 5 times/30 s exerting their maximum strength, and then performed a static grip, during which subjects were required to grasp the dynamometer for 10 s with 30% of maximum grip strength (F_{max}). This process was repeated until at least two out of five times of grip values were below the 50% of F_{max}, or any fingertip temperature monitored was below 8 °C in dynamic grip. For each test, only one condition was involved; a three-day rest was given in between two tests in order to let the subjects recover from the fatigue.

Each volunteer would do the grip strength first, then take a 10 min break. Once it was confirmed that the volunteer had recovered, the grip fatigue test could begin. According to the different physical ability of subjects, the fatigue test would last 15–40 min.

2.7. Comparative studies on data processing of grip fatigue

Concerning the fact that there was no common evaluating standard for the identification of grip fatigue of EVA gloves, this article improved the processing methods of fatigue on the basis of existed research (Ding et al., 2005, 2009), using the work generated during the process of grasp as an evaluation index. Fig. 2 shows the real-time curve of grip strength. Acquisition frequency was 5 times/s. Compared with the change of grip strength, the acquisition cycle of 0.2 s was short enough to ensure that the force of sensors within each cycle was constant. Thus, it was natural to consider d that the strain S of the dynamometer within each acquisition cycle was constant.

$$s_n = F_n/e \tag{1}$$

where e was the strain rate of sensors in dynamometer. It was a constant and with N/m as its unit; s_n was strain of gage in the n-th

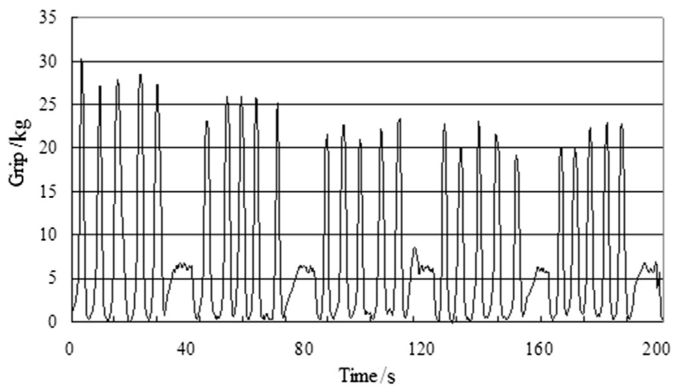


Fig. 2. Real-time curve of grip force.

acquisition cycle with unit m; F_n was the n-th grip value collected by the grip acquisition system with Newton units. The work generated by force of grip during each acquisition time was

$$W_n = F_n * s_n = (F_n)^2 \big/ e \tag{2}$$

where W_n was the work in the n-th acquisition cycle. Its unit was *Nm.* Therefore,

$$W = \sum_1^n W_n = \frac{1}{e} \sum_1^n (F_n)^2 \tag{3}$$

Eq. (3) manifested that the amount of work done was relevant to the strain rate of foil gage (e) in the dynamometer and grip values collected in the grip measurement system. In order to eliminate the influence of e, this article used the method of dividing experimental data by control data to eliminate e, thus, work was only related with grip value.

Fig. 3 shows the comparison of fatigue processing methods. Fatigue was calculated by impulse method and work method, respectively, and then normalised. Compared with subjective votes of the subjects, it was found that the work method was more preferable.

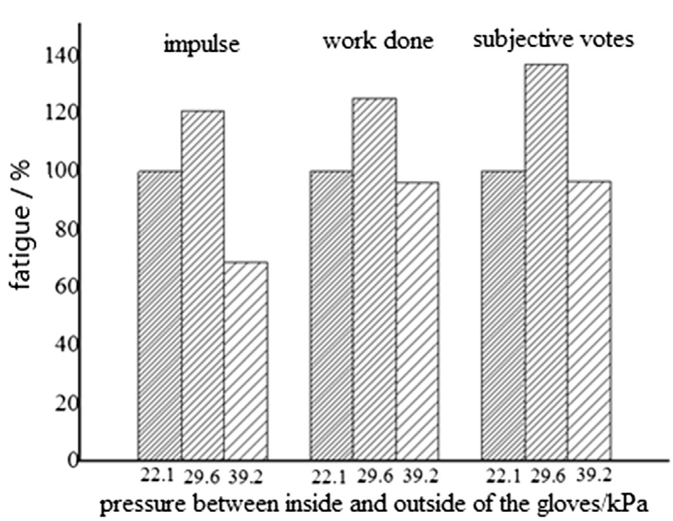


Fig. 3. Comparison of fatigue processing methods.

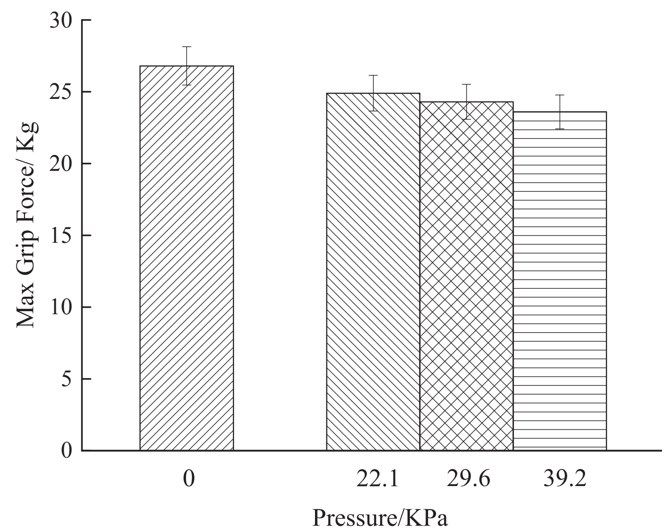


Fig. 4. Treatment Group I: Comparison of maximum grip strength.

3. Results

3.1. Grip strength

3.1.1. Effects of pressure on maximum grip strength

According to the results of our first treatment condition that is illustrated in Fig. 4, glove pressure is shown to have considerable effects on the maximum grip strength. Specifically, among the three pressurised conditions in treatment group I, the exposure to 22.1 kPa had little effect on the reduction of maximum grip force ($p > 0.05$). Increasing the pressure to conditions of 29.6 kPa and 39.2 kPa showed significant effects ($p < 0.05$). However, there were no significant differences among the three pressurised conditions of group I ($p > 0.05$).

3.1.2. Effect of low-temperature bar on maximum grip strength

Treatment group II, illustrated below in Fig. 5, showed that grasping low-temperature objects slightly reduces the maximum

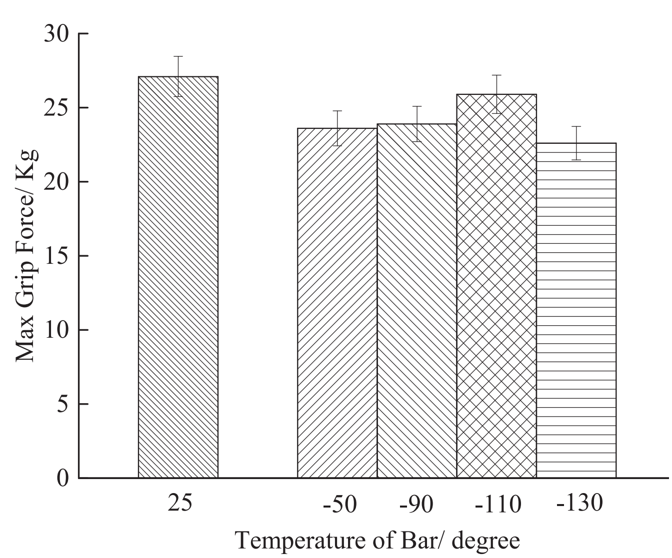


Fig. 5. Treatment Group II: Comparison of maximum grip strength.

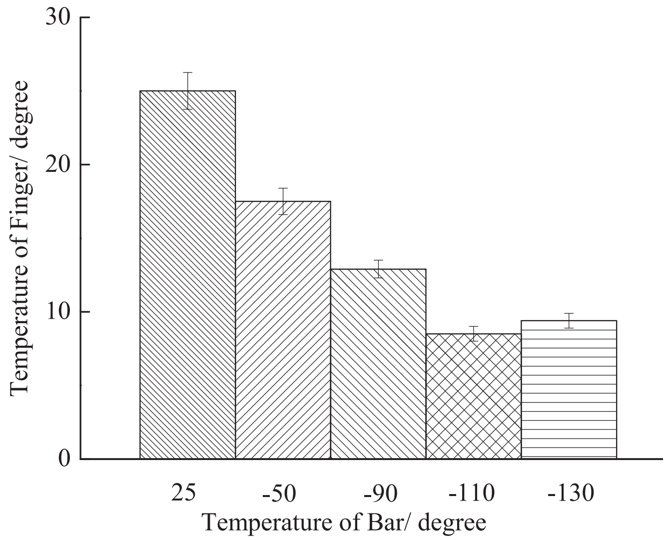
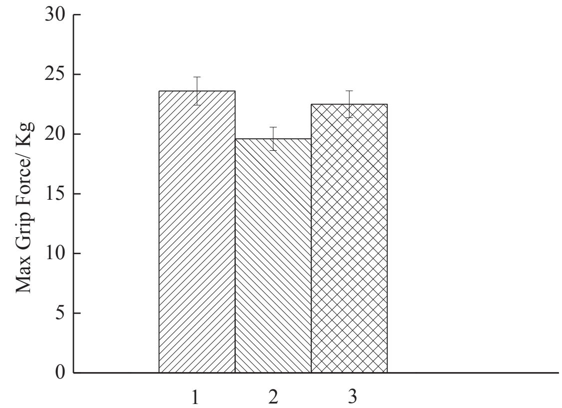


Fig. 6. Treatment Group II: Comparison of finger temperature change at the end of each experiment.



Note: 1: Unpressurised, temperature: -50 °C, AT: 25c; 2: pressure: 39.2 kPa, bar temperature: -50 °C, AT: 25c; 3: pressure: 39.2 kPa, bar temperature: -50 °C, AT: -50c

Fig. 8. Treatment Group IV: Statistic analysis of F_{max}.

grip strength. To clarify, the low-temperature condition itself had an indistinct effect on the maximum grip strength ($p > 0.05$), and there were no obvious differences in terms of grip force among the four low temperatures ($p > 0.05$). Compared to the control group, finger temperature in treatment group II reduced dramatically ($p < 0.05$, Fig. 6). However, there were no significant reductions in finger temperatures at -90 °C, -110 °C, and -130 °C ($p > 0.05$).

3.1.3. Combined effect of pressure and low temperature on the maximum grip strength

According to Fig. 7, the combined conditions of low temperature and increased pressure reduced the maximum grip strength dramatically ($p < 0.01$). However, there were no differences among three conditions of treatment group III ($p > 0.05$).

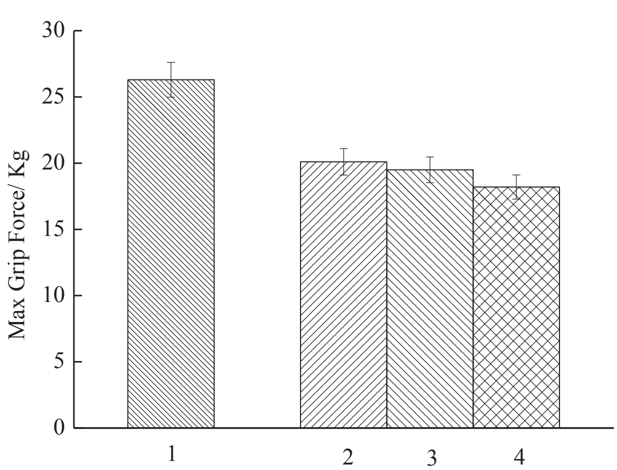
By comparing the selected data with the condition of -50 °C bar temperature from each experiment, we discovered that the maximum grip strength did not change significantly. Although the grip force might be reduced below 20 kg under conditions of high pressure and low temperature, this would readily enable astronauts to accomplish most EVA tasks on extravehicular missions.

According to the comparison of 1 and 2 in Fig. 8, pressure had a profound effect on maximum grip strength. Further analysis of 2 and 3 indicated that the maximum grip strength would not decline as long as the pressure was constant, even if the environmental temperature was lower than average conditions. Therefore, in terms of maximum grip strength, the major influential factor was the pressure inside the glove, and the effect of combined factors was no greater than that of any single factor.

3.2. Grip fatigue

3.2.1. Effect of pressure on grip fatigue

According to Fig. 9, the addition of pressure had an evident effect on grip fatigue ($p < 0.01$). Compared to the working capacity in control group, the capacity declined in each condition of the treatment group I, ranging from 23 to 37%. However, there were no



Note: 1: control; 2: Pressure: 39.2 kPa, Bar Temperature: -50 °C; 3: Pressure: 39.2 kPa, Bar Temperature: -110 °C; 4: Pressure: 39.2 kPa, Bar Temperature: -130 °C

Fig. 7. Comparison of F_{max} in treatment Group III.

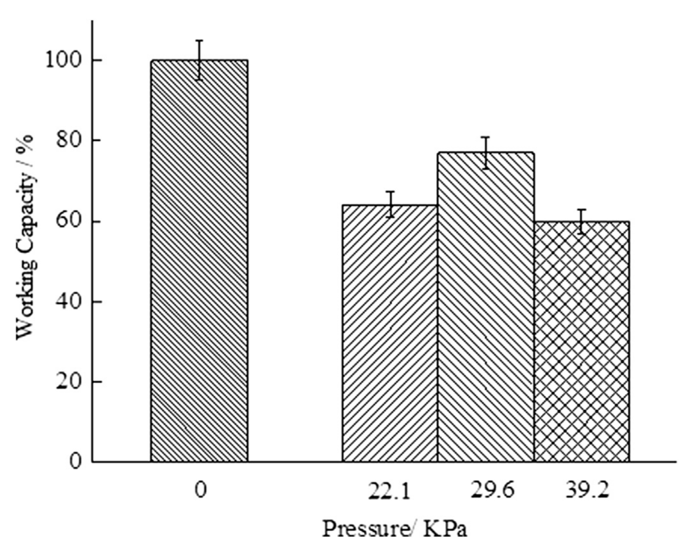


Fig. 9. Experiment I: Comparison of working capacity.

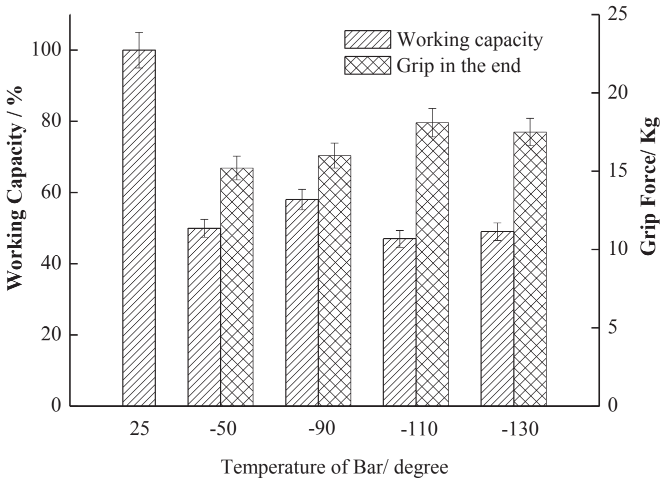
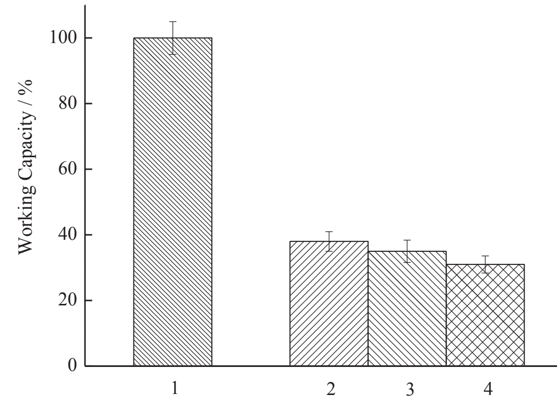


Fig. 10. Treatment Group II: Comparison of working capacity.



Note: 1: Control group; 2: Pressure: 39.2 kPa, Bar Temperature: -50 °C; 3: Pressure: 39.2 kPa, Bar Temperature: -110 °C; 4: Pressure: 39.2 kPa, Bar Temperature: -130 °C

Fig. 12. Treatment Group III: Comparison of working capacity.

distinct differences between the three conditions ($p > 0.05$).

3.2.2. *Effect of low temperature on grip fatigue*

Fig. 10 revealed that grasping low-temperature objects affected grip fatigue significantly ($p < 0.01$). Compared to the working capacity of the control group, the capacity of the treatment group II was reduced 50% approximately on average, but there were no significant differences among four temperatures, −50 °C, −90 °C, −110 °C, and −130 °C ($p > 0.05$).

By comparing the dynamic grip strength at the end, the dynamic grip strength was determined to be no less than half of the maximum grip strength under the condition of −110 °C and −130 °C, which allowed volunteers to keep grasping. However, the finger temperature had already reached the study termination criteria (8 °C, Fig. 11), thus the trial was terminated and volunteers were unable to continue testing. In contrast, under the condition of −50 °C and −90 °C, the finger temperature had not reached the cessation criteria, while the end grip strength was comparatively low. This allowed us to conclude that trial volunteers ended the experiment due to the hand fatigue.

3.2.3. *Combined effect of pressure and low-temperature on grip fatigue*

According to Fig. 12, the working capacity of hands was reduced below 40% of that in the control group under the combined condition of pressure and low temperature. This condition allowed hand fatigue to occur easily. However, there were no obvious differences among three conditions of the treatment group ($p > 0.05$).

Interestingly, by comparing the selected data with −50 °C bar temperature (Fig. 13), a totally different conclusion was drawn. Comparing 1 and 2, we found that pressure had an imperceptible effect on working capacity, while comparing 2 and 3, environmental temperature had an extreme effect on working capacity of hands.

4. Discussion

4.1. *Strength*

R. Bishu mentioned in his NASA report that when a certain type

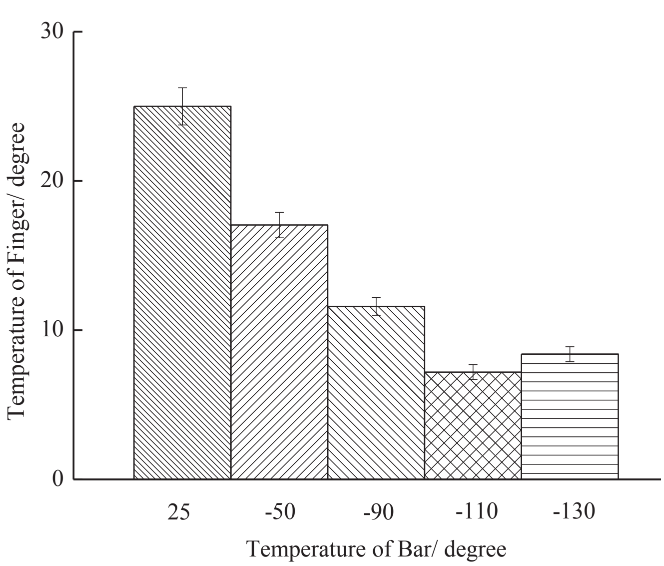
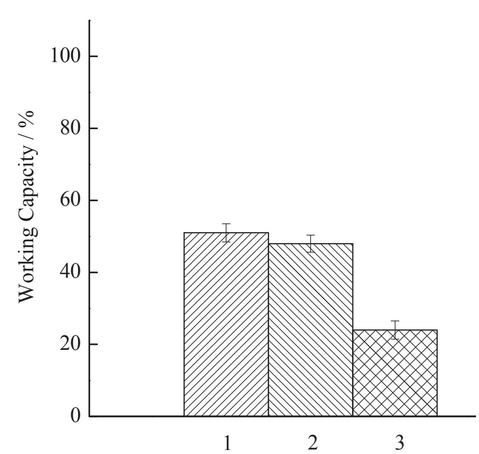


Fig. 11. Treatment Group II: Comparison of finger temperature change at the end of fatigue experiment.



Note: 1: Unpressurised, bar temperature: -50 °C, AT: 25 °C; 2: Pressure: 39.2 kPa, bar temperature: -50 °C, AT: 25 °C; 3: Pressure 39.2 kPa, bar temperature -50 °C, AT: -50 °C

Fig. 13. Treatment Group IV: Data analysis of working capacity.

of EVA glove pressurised to 29.5 kPa, the maximum grip strength would reduce to around 14 kg; when unpressurised, around 22 kg; and when pressurised, more than 29.5 kg, no obvious additional reduction (Bishu and Glenn, 1995). Even though there were numerical value differences, the general tendency of the report's result was consistent with that of our study, which illustrated that pressure indeed had an effect on grip strength. The major cause of the grip strength decline was the inner and outer pressure difference of the glove, which put the glove in a state of expansion. Due to the expansion, the glove folds would generate resistance, which opposed the working direction of the glove, and counteracted partial grip strength, resulting in a declining grip. Moreover, Fig. 4 shows that the mean of maximum grip has a slight decline, with the pressure increase, yet it is non-significant. The reasons may be: (a) expansion of the glove has small differences between the different pressures, which means the reaction between the lever and the fingers changed little; (b) the value of resistance is far less than the grip strength; it would be covered by the strength differences of volunteers; (c) the musculoskeletal system has not changed in grip strength with different pressures. Therefore, there were no obvious differences among diverse pressure levels, which was consistent with O'Hara's study result (O'Hara et al., 1988).

The result of the temperature-grip force experiment indicated that the finger skin temperature dropped greatly, but within a short time, temperature would not cause the grip strength to decline dramatically. Because the maximum grip strength was estimated within a short period, the finger skin temperature did not decline under 8 °C, even though the temperature was −130 °C. Because human tissue is good conductor of heat, and the circulation of the blood balances the body temperature, even if the surface temperature is low, the core temperature in muscle tissue will not fall. This is better to ensure the activity of muscle tissue. Furthermore, study volunteers did not report painful levels of coldness, and their finger temperature could recover quickly. Hence, the interference of low temperatures on grip force was less than that of pressure. Although there is no literature regarding this field, according to Qiuqing Geng's study (Geng et al., 2001), finger temperature would drop below 10 °C three to 5 min after the finger touched low-temperature objects, which might cause numbness and/or piercing pain of the extremities (initial temperature was 20 °C). In this experiment, our study volunteers actually spent much less time touching the grip bar than that in the literature, while the glove had a certain isolation, which was sufficient to maintain the temperature of the fingers. Therefore, the results of grip strength were credible.

4.2. Fatigue

Hand tolerance to fatigue has an obvious decreasing trend as the pressure increased, which was identical to O'Hara and Bishu's test results (O'Hara et al., 1988; Bishu and Glenn, 1995). The reasons may be: (a) glove resistance always exists in the tests; (b) muscles could not get sufficient rest, and maximum grip strength falls faster than a no-pressure state. Compared with the maximum grip strength, the gap between pressure and non-pressure becomes greater. Yet, for different pressure, the difference is not obvious, because the situation of force is basically identical.

The tolerance to fatigue was severely affected by temperature, but the successive decline of the temperature did not cause significant change of working capacity. Due to the particularity of the fatigue evaluation method, experiment II was divided into two situations. (a) When the temperature was very low (−110, −130 °C), heat would be lost to the environment due to the difference in temperature during the prolonged fatigue tests. The heat of the fingers, produced in blood and tissues, was unable to compensate the loss of heat in the environment, and the finger temperature was significantly reduced. As a result of this reduction in finger temperature, tingling, stiffness and other stress reactions were produced. These results led to a great decrease of working time, which affected the number of cycle (n) of fatigue evaluation and resulted in a decrease of working amount. (b) In another low temperatures (−50, −90 °C), the human body's metabolic heat could still remain at the finger temperature, so the experiment did not reach the termination conditions for low finger temperature. In this case, the evaluation of the impact of the fatigue was mainly responsible for the reduction of the grip force, which was similar to the pressurised condition. Thus, the experiment revealed that when the low temperature reached a certain value, the defined loss of astronauts' working ability would depend on both the low temperature or muscle fatigue, depending on the circumstances of the experiments.

4.3. Combined factors

Based on the results of horizontal comparison, we discovered that pressure was the dominant influential factor on the maximum grip strength, while the temperature had a slight effect. This paper argues that because the time period of the maximum grip strength test was too short, the finger temperature did not reduce to a defined level of intolerance, and thus, would not affect finger activities. Therefore, the contact of hand and glove due to the glove stamping was the main reason of the decline of the grip force.

Additionally, this paper argues that, for a long period of extravehicular activity, certain thermal protective concern of the palm side of the hand may be appropriate, which helps to improve the comfort of the palm to maintain the grip ability of hand. However, reducing the pressure inside the glove and improving joint structure are the main methods to solve the grip problem.

The circumstance of combined pressure and low temperature has obvious effects on fatigue. Data showed that grip was basically reduced 60–70%, and it even reduced to about 25% in experiment IV, which showed that when astronauts were doing extravehicular tasks, the main problem was the decline of tolerance capacity. From the statistical analysis of EVA tasks, we found that more than 10 cases of extravehicular tasks explicitly mentioned cold extremities, numb, and fatigue. For example, on 25 June 25 1993, at the 110th World Extravehicular Activities, the astronauts from the US were forced to suspend the extravehicular activity, because their hands were cold, numb and painful (Zhang et al., 2011). We could be sure that the astronaut's body quality was very good, because they had already undergone strict training on the ground before the task. But the low temperature in space was still beyond their expectations. We are curious about what kind of roles the low temperature had. The horizontal contrast of the results indicated that when the ambient temperature is lower than 110 °C the effect of temperature on working capacity is more obvious than that of pressure, which seriously affected the assessment of fatigue. Especially in the experiment IV, when the back side hand temperature decreased, the amount of working capacity reduced by half of the control provided by experiment II. The reason for this situation might be due to loss of heat from the back side of the hand, which resulted in an expedited decrease of fingertip temperature. This would cause earlier termination of the experiment, and would further reduce the number of working cycles. Therefore, for long-period extravehicular missions, in addition to emphasis insulation of the palm side of the hand, targeted thermal protection of the back-side of the hand is also necessary to effectively enhance astronauts' working duration and efficiency.

5. Conclusions

From the system study of maximum grip strength and grip fatigue of EVA gloves under combined factors (low-temperature, pressurised condition), the following points provide a summary:

(1) The major effect of the maximum grip strength was the pressurised state of the glove, while temperature had a lesser effect;
(2) Low temperature and pressure might affect the working capacity of the astronauts. However, pressure mainly caused fatigue, while temperature mainly affected the working time;
(3) Thermal protective performance of the back-side of hand had a key role enhancing astronauts' working time and their tolerance capacity.

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Muscle weakness is related to slip-initiated falls among community-dwelling older adults

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ABSTRACT

The purposes of this study were (1) to investigate the relationship between muscle weakness and slip-related falls among community-dwelling older adults, and (2) to determine optimal cut-off values with respect to the knee strength capacity which can be used to identify individuals at high risk of falls. Thirty-six healthy older adults participated in this study. Their muscle strength (torque) was assessed at the right knee under maximum voluntary isometric (flexion and extension) contractions. They were then moved to a special treadmill. After walking regularly five times on the treadmill, they experienced an identical and unannounced slip during walking on the treadmill with the protection of a safety harness. This treadmill could be considered a *standardized* platform, inducing an unexpected slip. Accuracy of predicting slip outcome (fall vs. recovery) was examined for both strength measurements (i.e., the strength capacity of knee extensor and flexor) using univariate logistic regressions. The optimal cutoff values for the two strength measurements were determined by the receiver operating characteristic analysis. Results showed that fallers displayed significantly lower knee strength capacities compared to their recovery counterpart (1.10 vs. 1.44 Nm/kg, $p<0.01$, effect size Cohen's $d=0.95$ for extensor; 0.93 vs. 1.13 Nm/kg, $p<0.05$, $d=0.69$ for flexor). Such results suggested that muscle weakness contributes to falls initiated by a slip during gait. Our findings could provide guidance to identify individuals at increased risk of falling using the derived optimal cutoff values of knee strength capacity among older adults.

1. Introduction

Falls are a significant health and medical problem facing the growing population of elderly (Tinetti, 2003). Slip-related falls contribute about 40% of all outdoors falls among seniors, which often cause serious injuries such as hip fractures (Luukinen et al., 2000; Stevens et al., 2006). Logically, it is urgent to understand the causes contributing to falls in order to develop efficient fall risk assessment tools and to design effective interventions for reducing falls.

Though it is well accepted that aging is associated with a progressive decline in overall mechanical muscle function (Goodpaster et al., 2006; Skelton et al., 2002) and muscle weakness has been implicated as a risk factor for falls, sound evidence regarding the extent to which the muscle weakness directly and independently relates to falls in older adults is largely lacking. The causal-effect relationship between muscle weakness and falls among older adults is still unclear. It was reported in one study that older fallers demonstrated less muscular strength (−15%) than their non-faller counterpart (Perry et al., 2007). A meta-analysis also concluded that muscle weakness should be one of risk factors leading to falls in older adults (Moreland et al., 2004). However, other studies showed minimal or no differences in strength between fallers and non-fallers (Daubney and Culham, 1999; Lipsitz et al., 1994; Skelton et al., 1994). A recent review article suggested that the evidence for the cause and effect link between muscle function and balance performance in older population is still weak (Orr, 2010).

Several possible reasons could contribute to such inconclusive causal-effect connections between muscle weakness and falls. First, the traditional self-report method collecting the real-life falls utilized in previous studies is subjected to inaccuracy, bias, and omission resulting from deteriorated memory or cognitive dysfunction in seniors (Moreland et al., 2004), and decreasing the reliability of data on fall incidence (Jenkins et al., 2002). Second, the physical activity level and the exposure to possible fall hazards are factors affecting the likelihood of falling in older adults. The self-report method does not account for these factors, possibly leading to underestimation of actual fall counts (Graafmanc et al.,

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2003; Wijlhuizen et al., 2010). There could be a trade-off between the exposure to fall hazards and the risk of falls among older adults (Horlings et al., 2008). For instance, those who are physically inactive might be more prone to falls due to physical limitations, but may also have the least exposure to conditions that might induce falls; while the most active ones, who might be less prone to falls, have high exposure to fall hazards leading to high likelihood of falling. Third, the self-reported data often lack information on the specific details (like types and circumstances of falls) of the actual falls (Feldman and Robinovitch, 2006), which could vary considerably from person to person. For example, muscle strength may not be as effective for the falls resulting from dizziness or orthostatic hypotension as for falls caused by external perturbations (such as slips or trips). Without considering or controlling for the circumstances of falls and level of the exposure to fall hazards, it is very difficult, if not impossible, to precisely investigate the relationship between muscle weakness and falls.

Last, the (retrospective or prospective) falls collection using self-reported methods were usually a significant period (like months) away from the evaluation of muscle strength (Horlings et al., 2008; Moreland et al., 2004). As muscle strength/power decline is a serious problem among older adults (Goodpaster et al., 2006; Skelton et al., 2002), the muscle strength measured could be substantially different from the one at the instant when the fall occurs. This mismatch raises another major concern as to how accurately the findings derived from the information collected at different time instants reflect the real causal-effect linkage between fall incidences and the muscle weakness. The only way to truly quantify the relationship between muscle weakness and falls is to evaluate how all subjects respond to the same gait perturbation administered in a controlled laboratory condition and to evaluate the muscle strength performance at the same time as the laboratory-induced falls.

Treadmills with the capability of exerting external perturbations on human gait have been broadly used in fall-prevention related studies towards both healthy adults and individuals with movement disorders. For instance, special treadmills were employed to improve balance compensatory responses during walking in young (Yang et al., 2013) and older persons (Shapiro and Melzer, 2010). In another study, an incremental speed-dependent treadmill was used to reduce postural instability and fear of falling in persons with Parkinson's disease (Cakit et al., 2007). These treadmills can produce a simulated perturbation (either slip or trip) by suddenly altering the belt speed when the subject is walking on it. The change in the belt speed can be delivered in a precisely-controlled manner. As a result, the intensity of the perturbation is identical across different trials and different subjects. Therefore, this type of treadmill provides a standardized platform inducing the same gait perturbations for different subjects. A standardized technique of creating slip perturbation allow us to eliminate the effects of other possible confounding factors (like the circumstance of a fall, duration between a fall and muscle function evaluation, etc.) on falls.

The purposes of this study were (1) to investigate the relationship between muscle weakness and slip-related falls among community-dwelling older adults, and (2) to determine optimal cutoff values with respect to the knee strength capacity which can be used to identify individuals at high risk of falls. After being measured for their muscle strength, all subjects were exposed to an identical risk of slip-related falling during gait upon a treadmill. We hypothesized that those who fell in response to the unexpected slip would demonstrate less knee muscle strength capacity compared with their recovery counterpart. The findings from this study could provide some guidance to develop effective muscle-strengthening-based fall-prevention training paradigms.

2. Methods

2.1. Subjects and experimental protocol

Thirty-six healthy older adults (71.3 ± 4.7 years, Table 1) participated in the experiment. All participants were free of any clinically significant history of musculoskeletal disorders, neurological disorders, orthopedic conditions, and cardiovascular conditions. As a safety precaution, all subjects were also screened for a significant cognitive impairment (Folstein et al., 1975) and an elevated risk of

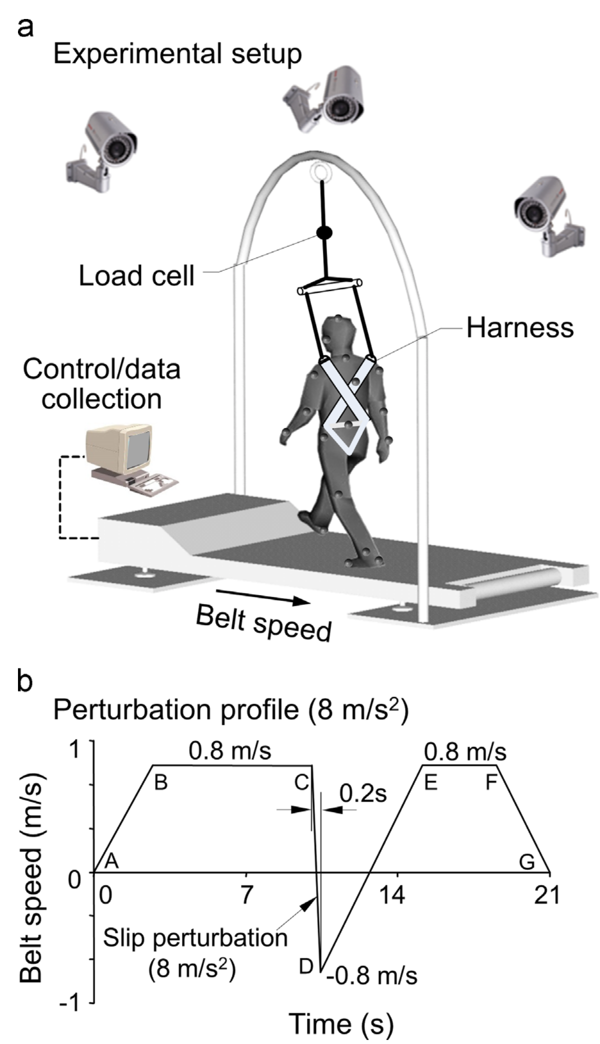

Fig. 1. Schematics of (a) the treadmill used to produce slip-like perturbation, and (b) a representative profile of the treadmill perturbation for a slip trial with the self-selected walking speed of 0.8 m/s and an acceleration of 8 m/s^2. The slip trial began with a 2-s ramp up (point A to B), followed by a steady state with a backward-moving belt speed of 0.8 m/s (B to C). After 10–12 regular steps in the slip trial, approximately 80–120 ms later than the touchdown of the leading foot, the top belt was suddenly accelerated forward within 0.2 s (point C to D) without the subjects' knowledge. Following the slip perturbation, the top belt speed slowly returned to backward direction at 0.8 m/s (point D to E). Subjects are protected by a full-body safety harness during all trials on the treadmill. Full-body kinematics is collected by a motion capture system from 26 reflective markers affixed to subjects' body.

Table 1
The demographics and self-selected gait speed in mean ± SD for both groups (fall vs. recovery).

Groups	Recovery (n=19)	Fall (n=17)	Pooled (n=36)
Age (years)	70.7 ± 4.8	71.9 ± 4.8	71.3 ± 4.7
Gender (male)	12 (63.2%)	5 (29.4%)	17 (47.2%)
Height (cm)	168.1 ± 9.7	161.7 ± 11.3	165.1 ± 10.8
Mass (kg)	77.3 ± 11.7	74.5 ± 21.8	76.0 ± 17.0
Self-selected gait speed (m/s)	0.97 ± 0.26	0.80 ± 0.23	0.89 ± 0.25

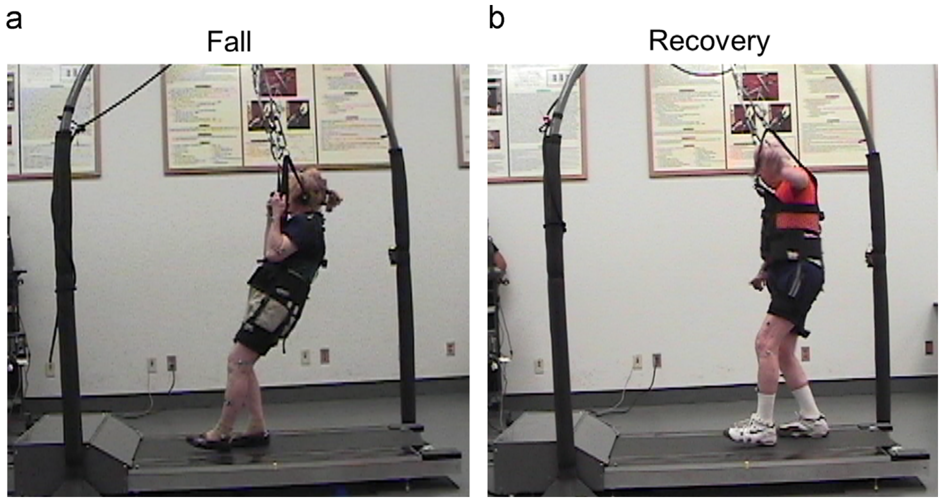

Fig. 2. Images showing two possible slip outcomes: (a) fall and (b) recovery. Following the occurrence of the slip, subject in (a) lost the balance and fell backward after an unsuccessful recover stepping. Approximately 84% (> 30%) of her body weight was supported by the harness after the recovery stepping. Conversely, subject in (b) was able to reestablish his balance by taking a recovery step. The peak load cell force was 12% (< 30%) body weight.

fracture during the slip perturbation (Thompson et al., 1998). All of the participants gave written informed consent which was approved by the Institutional Review Board.

2.2. Evaluation of muscle strength

It has been reported that the knee muscle strength can be used to represent the overall muscle strength among adults (Bohannon, 2008). Further, the important role of knee joints in resisting slip-related falls has been analytically (Yang and Pai, 2010) and empirically proven (Cham and Redfern, 2001). Therefore, the strength capacities (joint torque under isometric condition) were evaluated for all subjects on their right knee upon an isokinetic dynamometer (Biodex System 3, Shirley, NY). During muscle evaluations, subjects were seated in the dynamometer chair with their trunk and right thigh stabilized with safety belts to avoid any movement. The rotational axis of the dynamometer was aligned with the transverse knee-joint axis. One end of a length-adjustable rigid lever arm for measuring the knee joint was connected to the dynamometer. A shin pad in the other end of the lever arm was placed to the distal end of the tibia.

Following a 5-min general warm-up exercise, all subjects were seated in the testing position and were given a detailed explanation of the actions they would perform during the test. They also underwent a practice session on the dynamometer to experience the test conditions. During tests, subjects performed maximal voluntary isometric contractions of knee extensors and flexors for three repetitions each. The contractions lasted 7 s each and were separated by a 2-min rest interval. The peak torque normalized to body mass (Nm/kg) was recorded as isometric strength performance for each repetition. Three repetitions resulted in three peak torques. The average value of these three peak torques was used for analysis.

2.3. Slip perturbation

Following the muscle performance assessment, all subjects took a 10-min break and then stepped on a regular treadmill (Tracmaster, Newton, KS) over which each subject's comfortable walking speed was determined (Table 1). They were then moved to the ActiveStep treadmill (Simbex, Lebanon, NH) (Fig. 1a). They were informed that they would be performing normal walking initially and a “slip-like” movement on the treadmill “later” without knowing when and how that would happen. They were also told to keep looking forward during walking, and to try to recover their balance without grabbing onto the harness on any slip incidence, and then to continue walking.

After about five 15-s walking trials without slip perturbation on the treadmill, participants were exposed to the slip perturbation. Following 10–12 regular steps in the slip trial, approximately 80–120 ms later than the touchdown of the leading foot, without the subjects' knowledge, the top belt suddenly accelerated forward within 0.2 s, which induced a forward displacement of the subjects' base of support relative to their center of mass, generating an unexpected slip perturbation (Yang et al., 2013). The perturbation level was the same for all subjects as the acceleration being 8 m/s^2, providing a standardized framework to induce falls (Fig. 1b). Each subject underwent 14 slip trials in total. Only the first slip was analyzed in the present study. Full body kinematics data from 26 retro-reflective markers placed on the subjects' body were gathered using an 8-camera motion capture system (Vicon, Oxford, UK).

Upon all trials on the ActiveStep treadmill, a safety harness, connected by shock-absorbing ropes at the shoulders to an overhead arch, was employed to protect the subjects while imposing negligible constraint to their movement (Fig. 1a) (Yang and Pai, 2011). A load cell (Transcell Technology Inc., Buffalo Grove, IL) connecting to the ropes measured the force exerted on the ropes. The load cell force was recorded and synchronized with the motion capture and the video recording. Fall and recovery were two possible outcomes of a slip. Slip outcomes were classified as falls when the peak load cell force exceeded 30% of body weight and were unambiguously confirmed via visual inspection of recorded video (Yang and Pai, 2011) (Fig. 2a). Otherwise, the slip outcome was a recovery.

2.4. Statistical analysis

Independent *t*-tests were employed to identify if the muscle performance measurements (strength capacities of the flexor and extensor at right knee joint) demonstrated significant outcome-related difference. The effect size (Cohen's *d*) was also calculated for strength capacities to indicate the standardized difference between falls and recoveries. Univariate logistic regression determined the influence, across all subjects, of the knee strength capacities upon the odds of falls in response to the slip over treadmill. Predictive accuracy of the knee strength in classifying subjects as fall or recovery was assessed using sensitivity and specificity. Sensitivity was the proportion of those who were correctly classified as falls to all subjects who actually fell when experiencing the slip on the treadmill. Specificity equaled the proportion of all actual recoveries correctly classified as a recovery. Odds ratios were also calculated for each predictive variable based on the logistic regression coefficient and its standard deviation (SD) across all subjects. The optimal cutoff point for knee strength capacities (both extensor and flexor) to predict the slip outcome was identified by the receiver operating characteristic (ROC) analysis and Youden Index. The ROC curve illustrated sensitivity and specificity of knee strength capacities to predict the slip outcome upon the treadmill. The Youden Index was calculated as the difference between the sensitivity and 1 minus specificity. The best cutoff point for the knee strength capacities to predict slip-initiated falls was defined as the value which maximized the Youden Index. All statistics were performed using SPSS 22.0 (IBM, Armonk, NY), and a significance level of 0.05 was used throughout.

3. Results

All subjects experienced a balance loss in response to the unannounced slip. Seventeen subjects (47.2%) fell and 19 recovered successfully upon the slip induced on the treadmill. The knee strength capabilities in both directions were significantly lower among fallers than among those who did not fall (Fig. 3, $p < 0.01$ for extensor and $p < 0.05$ for flexor). The effect size Cohen's *d* was 0.947 and 0.689 for extensor and flexor, respectively, indicating a high practical significance (Table 2).

The knee extensor strength capability achieved significant level ($p < 0.01$) in predicting slip outcome with sensitivity of 64.7% and specificity 68.4% (Table 2). The overall prediction accuracy was 66.7% for knee extensor strength capacity. The flexor strength capacity was able to predict the slip outcome with an overall accuracy of 61.1% ($p=0.052$). The probability of falling upon the unexpected slip based on knee joint strength capacities can be calculated by the following expressions: $p(\text{fall})=\frac{1}{1+e^{-4.05+3.28\ \text{extensor}}}$ for extensor and $p(\text{fall})=\frac{1}{1+e^{-2.84+2.90\ \text{flexor}}}$ for flexor (Fig. 4). A decrease of 1SD (=0.36 Nm/kg across all subjects) in knee extensor strength capacity increased the probability of falling 3.23 times (Table 3). A decrease of 1SD (=0.29 Nm/kg) of knee flexor strength capability raised the odds of falling by a factor of 2.30 (Table 3). Both predictive models reached good classification as evidenced by the large area under the ROC curves (0.780 for extensor and 0.693 for flexor, Fig. 5a). Youden index indicated that the optimal cutoff values to classify fallers and those who did not fall were 1.05 and 1.10 Nm/kg for knee extensor and flexor, respectively (Fig. 5b).

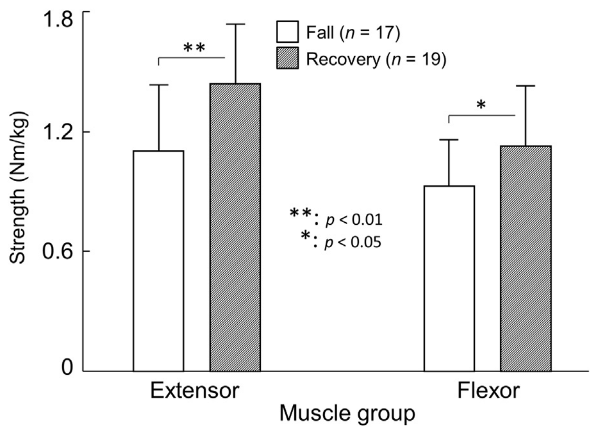

Fig. 3. Comparisons of the maximum voluntary strength (or torque) of the knee extensor and flexor under isometric contraction condition between falls and recoveries. Both muscle measurements are normalized to body mass. $^{**}p<0.01$; $^{*}p<0.05$.

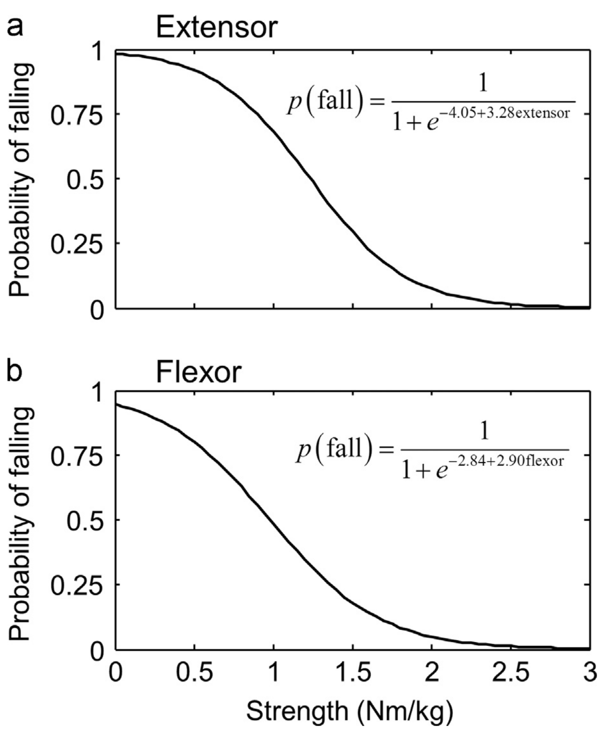

Fig. 4. Logistic regression in which the probability of fall from an induced slip on the treadmill is predicted using (a) knee extensor strength capacity and (b) knee flexor strength capacity.

4. Discussion

The results supported our hypothesis that muscle weakness associates with slip-related falls among older adults as evidenced by the significantly lower knee joint muscle strength capacity among fallers than among those who did not fall (Fig. 3). The optimal cutoff value of the knee muscle strength which could be used to identify those who are susceptible to high risk of falling is around 1.05–1.10 N m/kg.

The present study adopted a special treadmill which provides a standardized platform to expose all subjects to an identical-intensity slip perturbation during gait. Falls in response to the slip were identified by an objective criterion based on the measured load cell force. Furthermore, the muscle strength was evaluated at nearly the same time as when falls occurred. Consequently, any possible inaccuracy, bias, or ambiguity resulting from self-report methods of collecting real-life falls could be reduced or even eliminated in this study. The findings from this study could offer us a more accurate causal-effect link between the muscle weakness and falls among older adults than previous studies on account of self-reported fall-collection approaches.

Our results indicated that muscle weakness, particularly the knee strength capacity on both directions (extension and flexion), is related to slip-related falls in gait among older adults. Specifically, fallers demonstrated significantly less maximum knee strength in comparison to those who did not fall ($p<0.01$ for extensor and $p<0.05$ for flexor, Fig. 3). A unit decrease in knee extensor strength capacity would increase the odds of slip-related fall by a factor of 3.23. Similarly, the probability of falls after a slip ascends 2.30 folds if the knee flexor strength capability decreases by a unit. Our finding lends further support to previous studies

Table 3
Odds ratio for slip-related falls for both knee strength measurements.

Predictor	SD (Nm/kg)	Odds ratio *	95% CI
Extensor	0.357	3.23	1.78–5.87
Flexor	0.287	2.30	1.27–4.18

*: The odds ratio indicates the factor by which the fall probability increases with a decrease of 1SD in the predictor across all subjects.
CI: confidence interval.

Table 2
Prediction sensitivity, specificity, and likelihood ratio of slip outcomes (fall vs. recovery) from logistic regression analyses based on two predictive variables: strength capacity of knee extensor and flexor. Also shown is the effect size (Cohen's d) for each predictor. (CI: confidence interval).

Predictor	Sensitivity		Specificity		Overall prediction (%)	Likelihood ratio		p value	Effect size
	Value (% fall)	95% CI (%)	Value (% recovery)	95% CI (%)		Value	95% CI		
Extensor	64.7	41.3–82.7	68.4	46.0–84.6	66.7	2.05	0.97–4.33	0.009	0.947
Flexor	58.8	36.0–78.4	63.2	41.0–80.9	61.1	1.60	0.79–3.25	0.052	0.689

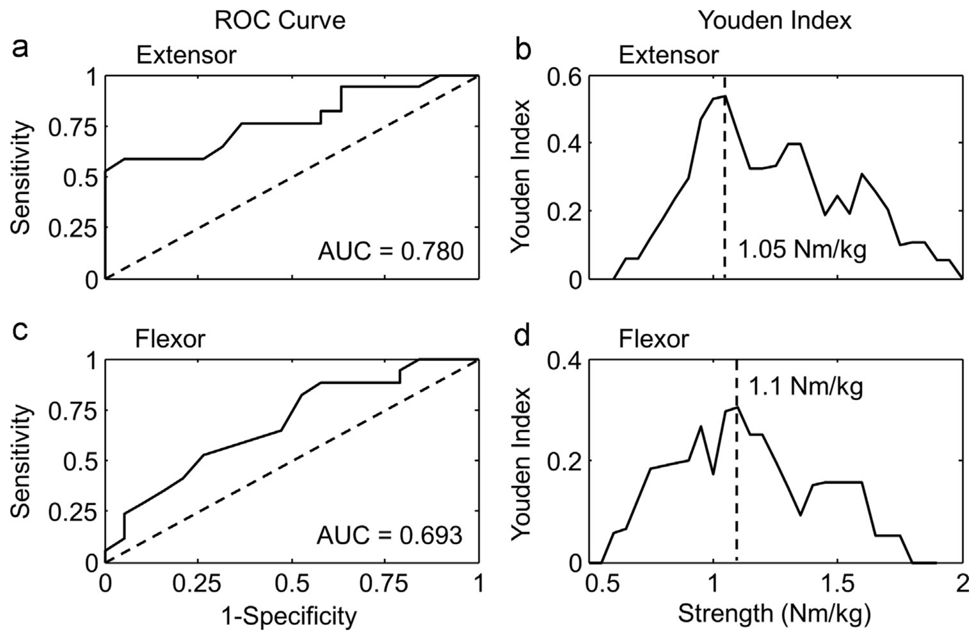

Fig. 5. The receiver operating characteristic (ROC) curve illustrating sensitivity and specificity of knee strength capacities of (a) extensor and (c) flexor to predict the slip outcome upon the treadmill. The area under curve (AUC) is 0.78 and 0.69 for knee extensor and flexor, respectively. Also shown is the change in the Youden Index values with (b) knee extensor and (d) knee flexor strength capacity ranging from 0.5 to 2.0 N m/kg. The Youden Index is calculated as the difference between the sensitivity and 1 minus specificity. The best cutoff point for the knee strength capacities to predict slip-initiated falls was defined as the value which maximized the Youden Index. In the present study, the best cutoff value for knee extensor strength is 1.05 N m/kg and 1.15 N m/kg for knee flexor.

which reported that muscle weakness is a key contributor to falls among older adults though the falls collection was based on the traditional self-report method (Horlings et al., 2008; Moreland et al., 2004).

Previous studies have found that repeated slip exposures could rapidly reduce the probability of slip-related fall within several trials among older adults (Marigold and Patla, 2002; Parijat and Lockhart, 2012). Such rapid reduction in falls within minutes, by no means, can be attributed to increases in strength, further implying that muscle weakness might not be related to falls, which seems contradictory to the findings of the present study. Such a contrast can be attributed to the differences in experimental protocols. During repeated slip exposure, the quick reduction in fall incidences were rather due to rapid proactive and reactive adjustments of the body posture and gait pattern to slip resulting from the prior slip experience (Marigold and Patla, 2002; Yang and Pai, 2013). The findings from the present study were, however, derived from the subjects' first exposure to a real-life like slip perturbation. All subjects had no experience of recovering from a slip or fall.

The link between muscle weakness and slip-related fall incidences could be explained by the necessary body reactions after a postural perturbation during gait. After a slip, to regain body balance and further prevent an actual fall, one must generate timely and sufficient corrective reactions during the recovery stepping (Cham and Redfern, 2001; Yang et al., 2009). Two major reactions to a slip perturbation have been reported previously (Cham and Redfern, 2001; Moyer et al., 2009). One reaction is a knee flexor moment which has the potential to drag the base of support towards the body's center of mass. Such reaction improves the dynamic stability and increases the chance of successfully recovering from the unexpected perturbation (Cham and Redfern, 2001; Yang and Pai, 2010). Another reactive response is the extensor moment from the recovery leg providing sufficient anti-gravity support to prevent a limb collapse (Cham and Redfern, 2001; Pai et al., 2006). If one can produce great muscle strength, the chance to retard and even reverse the falling after the slip would increase, reducing the probability of falling.

Through further investigation of the knee muscle strength capacities, we proceeded to the determination of cutoff values that would be statistically successful in predicting elderly fallers and non-fallers when exposed to an unexpected fall. These threshold values appeared to be 1.05 Nm/kg for the knee extensor and 1.10 Nm/kg for knee flexor (Fig. 5). Based on the predictive models, one whose knee muscle strength is above the thresholds would have small probability of slip-related falls. Therefore, these cutoff values could become a target for any muscle strengthening programs.

Though our findings indicated that muscle weakness is a limiting factor for balance recovery after a slip perturbation among older adults, the question remains whether slip-related falls can be reduced or prevented by targeting this factor through exercise-based muscle strengthening interventions. To date, outcomes from strength training programs for individuals with high risk of falls are still inconsistent or even controversial (Melzer et al., 2004; Orr, 2010). It has been proposed that exercise interventions with muscle strengthening can reduce falls (Barnett et al., 2003). However, other studies indicated that muscle strengthening exercise is not effective to reduce falls (Lipsitz et al., 1994; Lord et al., 1995) and a meta-analysis found no coherent effect of strength training on falls in older adults (Horlings et al., 2008). Such mixed outcomes from exercise-based strengthening training could also be associated with the inaccuracy of collecting falls using a self-report method, the temporal delay between instants when collecting falls and when assessing muscle strength, and the exposure level to potential fall hazards. Therefore, to uncover the actual causal-effect link between muscle strengthening and fall reductions among older adults, a standard platform (like the treadmill used in the present study) to expose all subjects to the identical fall hazard is highly desired.

Our study has limitations. First, muscle functional performance was only assessed at the knee joint since knee joints play a critical role in resisting slip-related falls (Cham and Redfern, 2001; Yang and Pai, 2010). Both hip and ankle joints are also essential to recover the balance from a slip (Liu and Lockhart, 2009). It is unknown if the finding from this study could be generalized to these two joints. Given the fact that the knee muscle strength can be used to characterize the overall limb muscle strength (Bohannon et al., 2012), it is reasonable to speculate that the finding of this study based on the knee joint could be applied to other lower-limb joints as well. Second, only the right knee was assessed in the present study. This may affect the interpretation of our results. However, given the symmetry of the knee muscle strength between legs among healthy adults (Bohannon et al., 2012), such an effect could be limited. Third, muscle activities of knee extensors and flexors were not measured during strength tests and the slip perturbation. Hence, we were unable to further testify our findings by examining the muscle activity between groups. Last, our findings could be further verified by designing a longitudinal study. Specifically, we can monitor if a faller in the present study could recover their balance when encountering an identical slip after undergoing a muscle strength training program. All of these issues warrant our further investigations. Despite the limitations, our study, as the first known one in which the older adults were exposed to a large-scale treadmill-induced slip perturbation in gait, sheds light on the relation between muscle weakness and fall incidences among elderly.

In summary, the results of this study suggested that muscle weakness is related to slip-related falls among community-living older adults and the threshold value of the knee muscle strength which could identify those with high risk of falls is around 1.05–1.10 N m/kg. Theoretically, fall incidence can be reduced by firstly identifying the biomechanical factors that contribute to fall and then develop effective interventions to prevent falls. Findings from this study provide insights into these two aspects by providing a possible tool to target individuals with elevated fall risk and a practical basis to develop fall prevention training programs based on muscle strengthening.

Conflict of interest statement

None declared.

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Optimizing the physical ergonomics indices for the use of partial pressure suits

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ABSTRACT

This study developed an ergonomic evaluation system for the design of high-altitude partial pressure suits (PPSs). A total of twenty-one Chinese males participated in the experiment which tested three types of ergonomics indices (manipulative mission, operational reach and operational strength) were studied using a three-dimensional video-based motion capture system, a target-pointing board, a hand dynamometer, and a step-tread apparatus. In total, 36 ergonomics indices were evaluated and optimized using regression and fitting analysis. Some indices that were found to be linearly related and redundant were removed from the study. An optimal ergonomics index system was established that can be used to conveniently and quickly evaluate the performance of different pressurized/non-pressurized suit designs. The resulting ergonomics index system will provide a theoretical basis and practical guidance for mission planners, suit designers and engineers to design equipment for human use, and to aid in assessing partial pressure suits.

1. Introduction

Personal protective clothing (PPC) is equipment used to ensure the safety of wearers in extreme environments, such as high altitude, low-pressure conditions for pilots and high-temperature environment for firefighters. Williams et al. (1997) performed a series of experiments to study the influence of chemical protective clothing during various activities of sailors. When they marched at medium speed with heavy backpacks, it was found that the chemical protective clothing not only limited their flexibility and field of vision but also decreased cognitive performance, including prolonged reaction time and increased number of physical and cognitive errors.

In order to evaluate the performance of a new style of protective suit for firefighters, Coca et al. (2008) studied a series of ergonomics indices, such as the wearer's range of movement, ability to accomplish tasks, and comfort. They analyzed the ergonomic qualities of the clothing by comparing the variation of each ergonomics index under two conditions: wearing a new prototype firefighter ensemble (PE) with additional chemical/biological hazard protection and a standard ensemble (SE). They found that in spite of design features to enhance chemical/biological hazard protection, the PE design does not decrease the wearer's overall functional mobility compared to the SE. However, subjects seem to be more comfortable wearing the SE compared to the PE. These overall findings support the need for a comprehensive ergonomic evaluation of protective clothing systems to ascertain human factors issues. Berson (2002) found that pressurized clothing restricts the wearers' movement when inflated, affecting control of the ambulance and ability to perform emergency operations.

In order to increase the ability of pilots to efficiently fly within a U-2 cockpit, movement-related indices should be considered in the design phase of PPS. O'Hearn et al. (2005) studied the influence of Army cold weather clothing's operating dexterity as well as physical security and comfort. Based on their research, they established ergonomics evaluation methods and an ergonomics index. However, this clothing is used on the ground environment and is very different with pilot's PPS. Partial pressure suits (PPSs) are one type of personal protective clothing designed to ensure the safety of pilots when flying at high altitudes (Hu et al., 2008b). A PPS is worn

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Nomenclature

PPC	personal protective clothing
TP	target pointing
PDV	pull down the veil
DBL	drawing-back a leg
CJ	controlling-joysticks
AT	accomplishing time of task
B	buttons
BS	buttons and switches
RWRA	right wrist bar thumb side
RWRB	right wrist bar pinkie side
RKNE	right knee
RANK	right ankle
LELB	left elbow
RELB	right elbow
RSHO	right shoulder
TP1	AT of right arm with B group for TP
TP2	AT of left arm with BS group for TP
TP3	AT of right arm with BS group for TP
TP4	inverse orientation AT of right arm with BS group for TP
PPS	partial pressure suit
PDV1	movement of RWRA for PDV
DBL1	flexion angle of RKNE joint for DBL
DBL2	movement of RANK for DBL
CJ1	pushing forward of RWRA for CJ
CJ2	pushing left of RWRA for CJ
CJ3	pushing right of RWRA for CJ
RS1	maximum vertical movement of RELB for lateral lift
RS2	maximum vertical movement of RELB for forward extension
RS3	maximum vertical movement of RELB for backward extension
RS4	maximum horizontal movement of RELB for adduction
RS5	maximum horizontal movement of RELB for abduction
RS6	range of motion of RSHO in the coronal plane
RE1	motion angle of RELB joint
RH1	movement of RKNE
RH2	range of motion of right hip joint
RW1	movement of LELB
RW2	movement of RELB
GS1	maximum grip strength

by pilots to protect them from both high altitude hypoxia and hyperventilation. It is a potentially life saving piece of equipment when coupled with a high-altitude oxygen-supply protection system (Kozloski, 1994). A PPS utilizes the mechanical forces and ergonomics of the clothing to provide counter pressure for the body surfaces. As a result, the negative effects on the body from a pressurized oxygen-supply can be reduced, providing greater endurance (Berglund and Marklund, 2005).

In recent years, with the improved performance of fighter planes, the protective capability requirements of PPS have increased as well, leading to concerns about the tradeoffs between a PPS's function and efficiency (Færevik and Eidsmo Reinertsen, 2003; Murray et al., 2011). Ergonomics research on high-altitude partial pressure suits (PPSs) can provide evidence to develop an optimal ergonomics index that can be used to evaluate the design of PPS. Past research (Adams and Keyserling, 1996; Hu et al., 2008a, 2007; Liu et al., 1998) on PPS neglected two vital aspects: (1) The lack of a valid index system for PPSs based on engineers' design of safe and ergonomic protective wear. To date, there have been no studies researching indices based on human mechanics and anatomy. Therefore, it is useful to establish an integrated and valid ergonomics evaluation index system for PPSs that is primarily based on the environment, cockpit layout, flight operation tasks, human mechanics and anatomy. (2) The lack of research on optimization of a PPS ergonomics evaluation index. In order to increase efficiency while minimizing the costs and time for PPS evaluation, it is essential to optimize an index system to increase its practicality and functionality.

The present study focuses on optimization of an ergonomics evaluation index system. This system has three interrelated levels. Level 1 includes three ergonomics indices, level 2 includes 10 ergonomics indices and level 3 includes 23 ergonomics indices. Since there are many indices in this system, it would be too time-consuming to measure and analyze all of them, especially since some of them cannot be measured in a limited time frame. For example, when a PPS is pressurized, the wearer has only a short time before breathing becomes a problem due to external positive pressure, which would make it difficult to complete the required measurements. Therefore, the present research optimized the ergonomics evaluation index system using regression and fitting analysis. In this way it provided a more convenient and efficient way to evaluate the ergonomics performance of PPS.

A series of ergonomics experiments on PPSs were conducted to establish this systematic evaluation to improve the flight performance of pilots, their ability to perform tasks efficiently in a PPS and the ergonomics design of the human–machine interface in an aircraft cockpit.

2. Methods

2.1. Subjects

Based on pilot recruitment standards of China, twenty-one healthy right-handed Chinese males were recruited for this study. Females were not recruited since most pilots in China are male. The demographics and anthropometric parameters of the subjects are listed in Table 1.

2.2. PPS

Two different types of clothing were tested: conventional clothing (CC) and the partial pressure suit (PPS). The casual attire consisted of shorts and a vest, while the PPS was a capstan anti-G and counter pressure suit widely used by pilots (Fig. 1).

Table 1
The mean anthropometric data for all of the subjects.

Items	Mean	Std.	Min.	Max.
Age (yr.)	23.14	1.20	21	25
Height (cm)	169.48	2.73	165	175
Weight (kg)	62.52	4.99	56	77
Leg length (cm)	90.81	2.93	84	97
Lower leg length (cm)	39.86	2.67	34	44
Shoulder width (cm)	40.52	1.57	38	44
Knee width (cm)	9.89	0.93	9	13
Ankle width (cm)	6.37	0.63	5	8
Chest circumference (cm)	91.71	4.15	84	101
Thigh upper circumference (cm)	55.24	2.55	50	60
Trunk upright circumference (cm)	166.19	5.09	158	176
Upper arm length (cm)	31.24	1.95	28	34
Lower arm length (cm)	25.38	0.74	24	27

2.3. Ergonomics indices

The ergonomics indices considered in this study, shown in Table 2, were established from the studies of Hu and Li (Hu et al., 2007, 2008b; Li et al., 2013). All of the following indices have been shown to be effective for measuring the performance of PPSs. These indices can be classified into three levels. Level 1 includes three indices (dexterity for tasks, operational reach, and operational strength); Level 2 consists of ten ergonomics indices ranging from end-effort pointing performance to range of motion of the shoulder; and Level 3 is comprised of twenty-three elementary ergonomics indices including micro-movement analysis of a timed finger pointing exercise, a timed range of motion test for the movement of knees, and the time to vertically displace the elbow. In this study the functional relationships among ergonomics indices and the three levels were analyzed.

Table 2
The ergonomics evaluation index system for PPSs.

Ergonomics indices of level 1	Ergonomics indices of level 2	Ergonomics indices of level 3	Unit
Manipulation missions	Target pointing/TP	TP1	s
		TP2	s
		TP3	s
		TP4	s
	Pull down the veil/PDV	PDV1	mm
	Drawing-back the legs/DBL	DBL1	deg
		DBL2	mm
	Control of the joystick/CJ	CJ1	mm
		CJ2	mm
		CJ3	mm
Operational reach	ROM of shoulder joint/RS	RS1	mm
		RS2	mm
		RS3	mm
		RS4	mm
		RS5	mm
		RS6	deg
	ROM of elbow joint/RE	RE1	deg
	ROM of hip joint/RH	RH1	mm
		RH2	deg
	ROM of waist joint/RW	RW1	mm
		RW2	mm
	ROM of knee joint/RK	RK1	deg
Operational strength	Grip strength/GS	GS1	kg

2.4. Apparatus

2.4.1. Motion capture system

We utilized a three-dimensional video-based motion capture system (VICON460, England). Six infrared cameras were placed in a circle, which encompassed a full range view of all actions. The acquisition sample rate was 120 Hz. The equipment consisted of hardware (computer workstation, video cameras, etc.) and software applications systems (Polygon, Bodybuilder, for example) used to record and analyze body movements. Motion capture involves recording these movements via infrared video cameras and then reproducing them in a digital environment.

2.4.2. Target-pointing board

A mock-up of a real cockpit made up of a flat rectangular board with five buttons and four switches (Fig. 2) was used to simulate a flight mission. The board was fixed on a table with a gradient angle of 17° from the vertical plane. The length and width of the board were 800 mm and 600 mm, respectively.

Fig. 1. Partial pressure suit.

2.4.3. Hand dynamometer

A standard hand dynamometer (WCS−100II), composed of a sensor and digital display unit, was used to measure maximum grip strength. The scale spanned a range from 0 to 100 kg, with a precision of 0.1 kg.

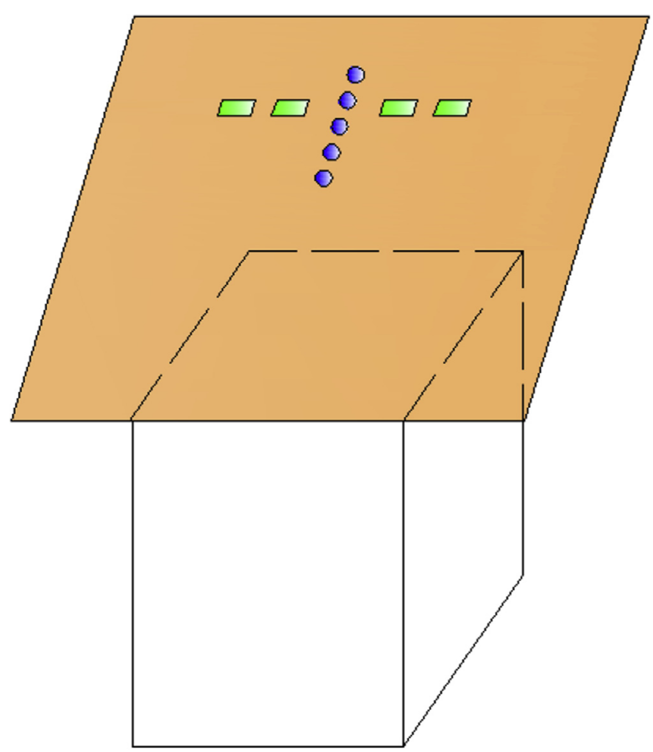

Fig. 2. Target-pointing board.

2.5. Experimental set-up and anthropometric landmarks

All tests were conducted at the Man-Machine-Environment System laboratory at Beihang University. Every subject completed the spectrum of tests randomly wearing both conventional clothing and a PPS. The subjects were given a 1-h rest period between tests, during the rest period, the subjects were required to sit or stretch their limbs and joints to relax their body. Each subject sat with an erect posture in the center of the motion capture area. The seat height and seat surface inclination are set similar with the seating in the cockpit. The anthropometric dimensions of the subject were measured prior to the experiment and used to select the appropriate PPS clothing size. After donning the PPS, the subject maintained the required sitting posture. Then a qualified laboratory assistant adjusted the PPS to ensure a proper fit. Finally, 39 reflective markers were attached to the subject by the assistant, each corresponding to an anatomical landmark. Fig. 3 shows the marker positions for an entire body capture. Formal tests were carried out after these preparations and each test was performed 3 repetitions. The detailed testing procedure has been previously described by Hu et al. (2008b).

2.6. Experimental design

2.6.1. Dexterity for tasks

2.6.1.1. Target pointing. Two types of tests were performed in order to optimize the ergonomics indices for PPSs on tasks with different levels of complexity. The subjects were divided into two test groups. The B group was placed in front of five buttons, while the BS group negotiated five buttons and four switches. The BS group's tests measured flexibility of the left and right arm and range of right arm extension, while the B group's tests measured the flexibility and extension of the right arm only. The tests required the subject to sit in front of a target-pointing board with his arm on an armrest. The subject was required to maintain erect posture at all times during the test. We measured the time taken to fully extend his arm, press down targets as quickly as possible, and then pull back his arm to the initial position. These actions were repeated five times and the subject was asked to not only touch the targets but also press down the buttons or accurately manipulate the switches. This test was designed based on the panel operations task. The time required to accomplish all tasks was defined as the accomplishing time of the task (AT). The following tests took place: The B group was required to point at a target with the right arm (TP1); The BS group pointed at a target with the left hand (TP2); The BS group pointed at a target with the right hand (TP3), while TP4 measured the inverse orientation time of pointing at a target with the right arm for the BS group.

2.6.1.2. Adjustment of the helmet. In the event of ejection from the cockpit, the pilot must be able to adjust his or her helmet. In this experiment the subject was asked to raise both arms as high as possible and then pull them down as far as possible. The test variable, defined as pulling down the veil (PDV1), was the maximal movement of right wrist bar little finger side (RWRB) (Fig. 4a).

2.6.1.3. Drawing-back the legs. This task was designed to measure the peak leg extension required to reach the rudder pedals and to determine if the PPS impeded the ability to bring the legs close to the seat when preparing for ejection. Both legs were first placed in a standard position where the relative angle of the thigh and lower leg was at 90°. Then the subject attempted to extend both legs and draw them back till the knees reached their maximum angle. These two test variables are shown in Fig. 4b.

2.6.1.4. Control of the joystick. While sitting upright, the subject was asked to push a joystick forward, then left, then right. Fig. 4c displays the three test variables: pushing forward of right wrist bar thumb side (CJ1), pushing left with the right wrist thumb bar side (CJ2), pushing right with the wrist bar thumb side to control the joystick (CJ3).

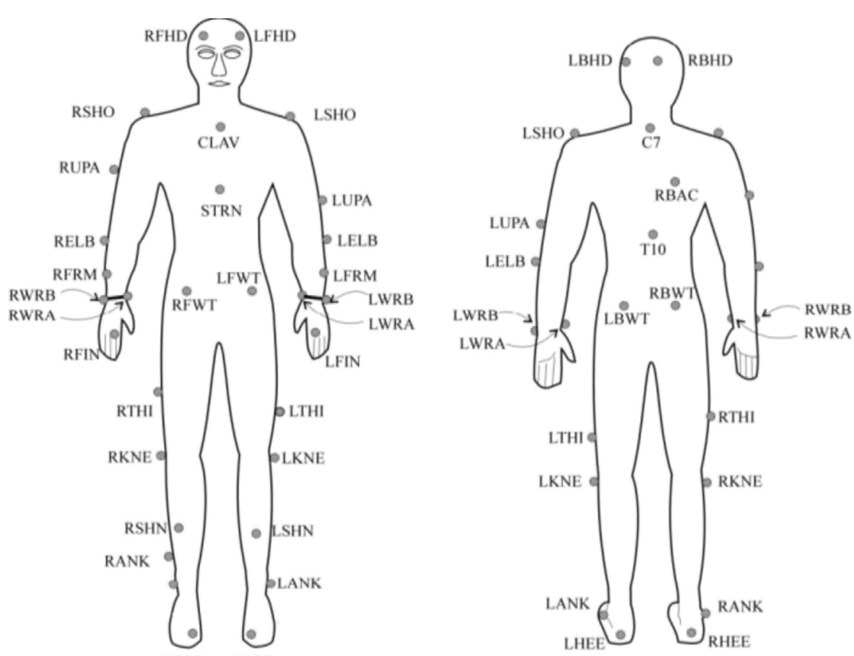

Fig. 3. Locations of the 39 reflective markers.

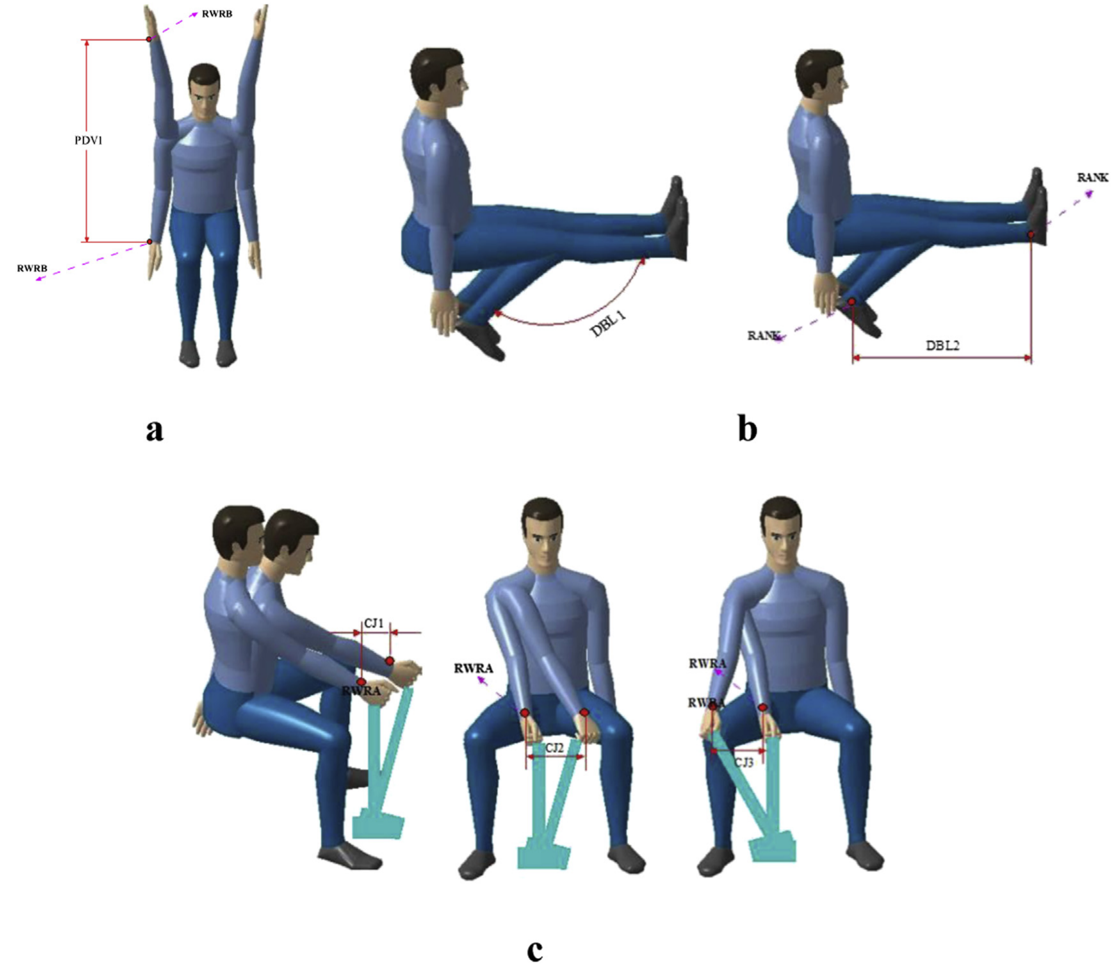

Fig. 4. Test variables of the manipulative missions for a) adjusting the helmet, b) drawing-back the legs and c) control of the joystick.

2.6.2. Operational reach

2.6.2.1. Range of motion of the shoulder. Measurements of the range of motion index included right arm lateral lift, fore/aft extension and adduction/abduction. The subject moved his arm in the specified plane without rotation while performing these tasks. The six test variables are shown in Fig. 5a.

2.6.2.2. Range of motion of the elbow. Keep the subject's upper arm extended downward and the range of motion of the elbow was measured when the subject was asked to move his forearm until the elbow reached its maximal flexion angle. Fig. 5b gives the definition of the test variables.

2.6.2.3. Range of motion of the hips. At first, the subject kept his right foot on the ground and his right knee joint at a 90° angle. Then the subject raised his right leg as high as possible.

2.6.2.4. Range of motion of the waist. Starting from an erect sitting position, the subject bent his waist laterally to the left and then to the right as far as possible without twisting.

2.6.3. Operational strength

2.6.3.1. Grip strength. While sitting with erect posture, the subject reached out with his right hand and grasped the hand dynamometer as firmly as possible (Fig. 6a).

2.6.3.2. Step-tread strength. While keeping the torso erect, the subject extended his right leg to step on the tread sensor (Fig. 6b).

2.7. Statistical analyses

The relationships between ergonomics indices were obtained via linear regression analysis using the statistical packages SPSS 12.0 and OriginPro7. The significance level was set at $p < 0.05$.

3. Results and validation

Tests validated whether or not the indices were significantly associated with PPS compared to conventional clothing (CC). Table 3 shows these comparison for each index variable. Results indicated that all the index variables were significantly affected by the use of the PPS ($p < 0.01$). The relationships among the indices were examined using regression analysis.

To validate whether or not the optimized ergonomics index system can efficiently evaluate the ergonomics performance of PPS a study which tested the range of motion, operational dexterity and grip strength of ten male subjects wearing PPSs under six different pressure conditions was conducted to determine their effects on pilots' operational performance using the optimized ergonomics index system.

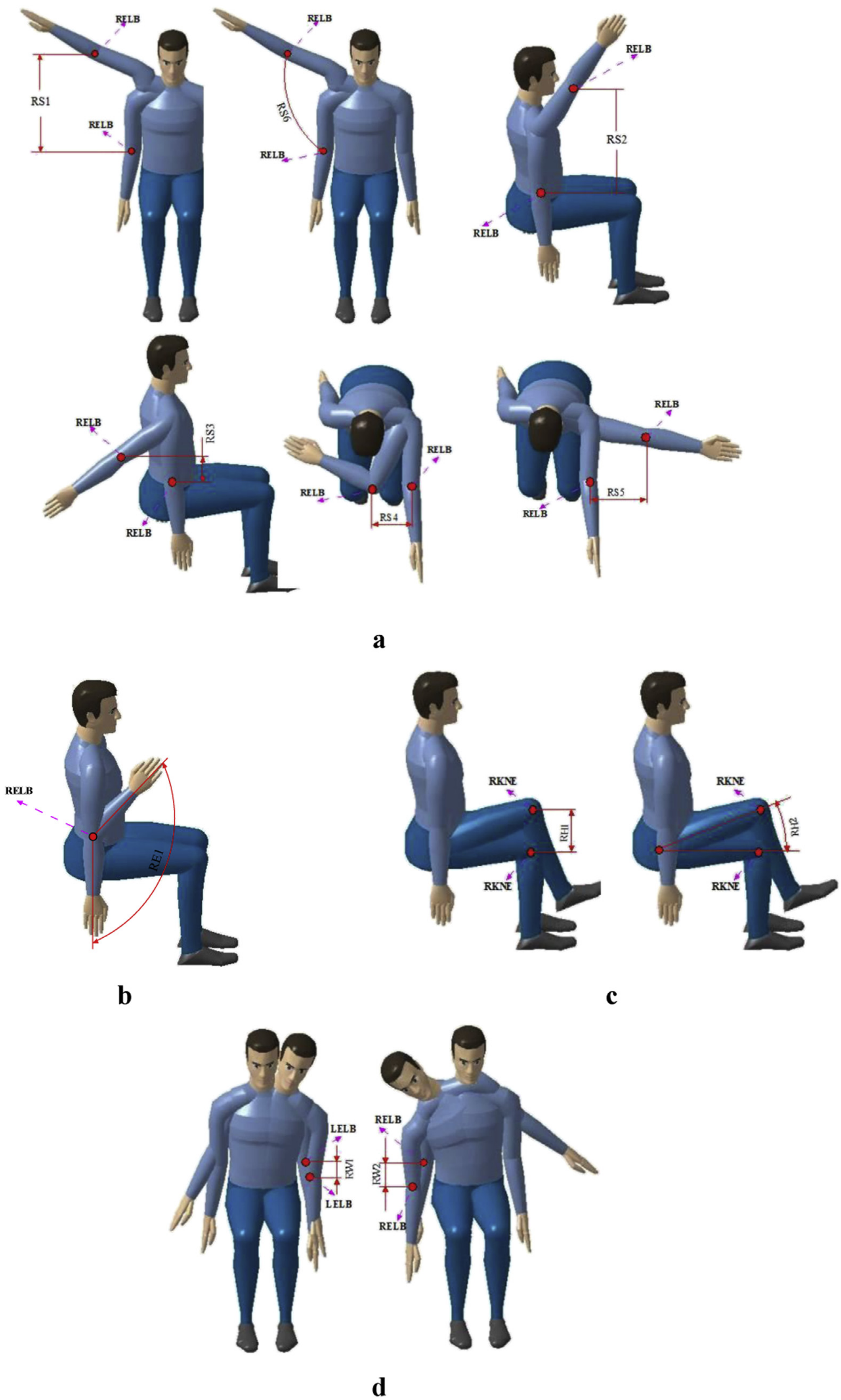

Fig. 5. Test variables of operational reach for ROM of a) shoulder joint, b) elbow joint, c) hip joint and d) waist joint.

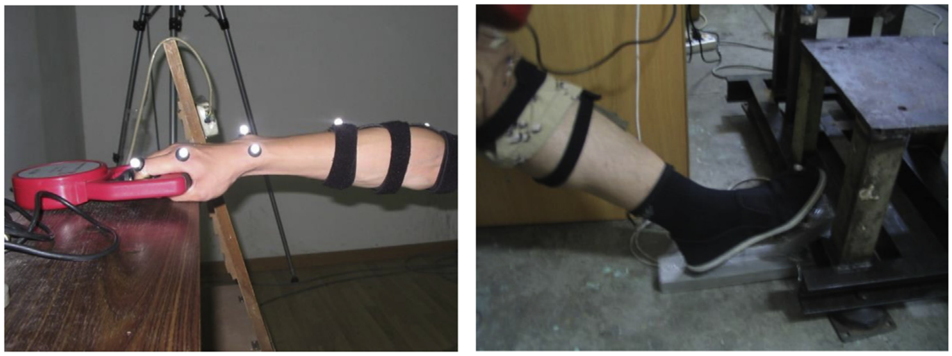

Fig. 6. a) Grip strength. b) Step-tread strength.

3.1. *Statistical analysis on ergonomics indices of level 3*

3.1.1. *Ergonomics indices of target pointing*

From the scatter plots of the BS group pointing at a target with the right index finger (TP3) versus pointing with the left index finger (TP2) and the inverse orientation of time to point with the right index finger (TP4) (Fig. 7), it is clear that both TP2 and TP4 were linearly related to TP3. TP3 can be considered as the independent variable of x, and TP2 and TP4 were the dependent variables of y_1 and y_2, respectively. The correlation coefficient for TP2 and TP3 was $r_1 = 0.894 > r_{0.01}(n-2)$ ($p < 0.001$), indicating that an effective functional relationship exists between TP2 and TP3. The correlation coefficient of TP3 and TP4 was $r_2 = 0.992$ and $p < 0.001$. In contrast, TP1 is not significantly linearly related to TP2, TP3 and TP4.

3.1.2. *Ergonomics indices of drawing-back the legs*

Fig. 8 shows that the flexion angle of the right knee for drawing back the leg (DBL1) was linearly related to movement of right ankle for drawing back the leg (DBL2) ($r = 0.06$, $p = 0.005 < 0.01$). Assuming DBL2 was the dependent variable of y and DBL1 was the independent variable of x, then DBL1 was significantly associated with DBL2. Using this equation, DBL2 can be derived from DBL1.

3.1.3. *Ergonomics indices of control of the joystick*

Pushing forward of right wrist bar thumb side to control a joystick (CJ1), pushing left with the right thumb bar side (CJ2) and pushing right wrist bar thumb side (CJ3) were found to be correlated. In our linear regression models (Fig. 9) the independent variable of x was CJ3; the dependent variables of y_1 and y_2 were CJ1 and CJ2, respectively. The results of the linear regression and variance analysis showed that CJ1 and CJ2 were positively correlated with CJ3. The results showed that CJ3 and CJ1 were significantly linearly correlated ($r = 0.634$, $p = 0.00202 < 0.01$), indicating that this equation would be useful as a predictive model. A positive correlation was found between CJ2 and CJ3 ($r = 0.639$, $p < 0.01$).

3.1.4. *Ergonomics indices of ROM of the shoulder*

3.1.4.1. Maximum vertical movement of the right elbow for lateral lift (RS1) and maximum angle of motion of the right shoulder (RS6).

Table 3
The statistical experimental data for PPSs.

Ergonomic indices of level 1	Ergonomic indices of level 2	Ergonomic indices of level 3	Unit	Experimental data	
				CC◆	PPS
Manipulation missions	Target pointing/TP	TP1	s	6.83 ± 1.45	7.20 ± 1.68★★
		TP2	s	13.55 ± 1.39	14.92 ± 1.58★★
		TP3	s	13.77 ± 1.97	14.90 ± 1.81★★
		TP4	s	12.96 ± 2.06	13.95 ± 1.75★★
	Pull down the veil/PDV	PDV1	mm	1069.13 ± 40.37	972.76 ± 50.69★★★
	Drawing-back the legs/DBL	DBL1	deg	125.80 ± 15.46	109.07 ± 9.54★★★
		DBL2	mm	645.10 ± 61.63	624.25 ± 56.96★★★
	Control of the joystick/CJ	CJ1	mm	186.00 ± 42.64	160.50 ± 36.87★★★
		CJ2	mm	223.69 ± 32.75	182.51 ± 28.69★★★
		CJ3	mm	299.70 ± 49.27	270.55 ± 53.66★★★
Operational reach	ROM of shoulder joint/RS	RS1	mm	612.62 ± 33.33	548.78 ± 46.14★★★
		RS2	mm	600.62 ± 33.33	549.63 ± 32.47★★★
		RS3	mm	163.58 ± 50.96	145.90 ± 49.74★★
		RS4	mm	330.51 ± 45.26	291.85 ± 43.98★★★
		RS5	mm	277.65 ± 68.59	231.50 ± 62.25★★★
		RS6	deg	134.72 ± 9.51	114.89 ± 14.64★★★
	ROM of elbow joint/RE	RE1	deg	117.40 ± 5.44	107.82 ± 6.25★★★
	ROM of hip joint/RH	RH1	mm	323.73 ± 43.65	268.36 ± 45.70★★★
		RH2	deg	49.79 ± 7.30	36.98 ± 9.07★★★
	ROM of waist joint/RW	RW1	mm	139.06 ± 32.13	116.79 ± 27.89★★★
		RW2	mm	157.69 ± 36.05	129.42 ± 32.14★★★
	ROM of knee joint/RK	RK1	deg	125.80 ± 15.46	109.07 ± 9.54★★★
Operational strength	Grip strength/GS	GS1	kg	42.89 ± 5.40	41.26 ± 5.35★★

The data are described in the form of Average and STDEV ($\bar{x}$±s).
Compared with ◆the control group, ★$p < 0.05$, ★★$p < 0.01$, ★★★$p < 0.001$.

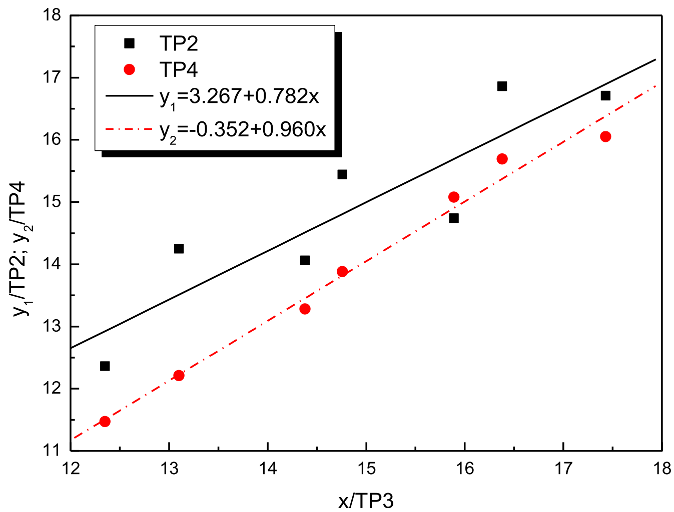

Fig. 7. Scatter diagram and regression lines of TP2, TP3 and TP4.

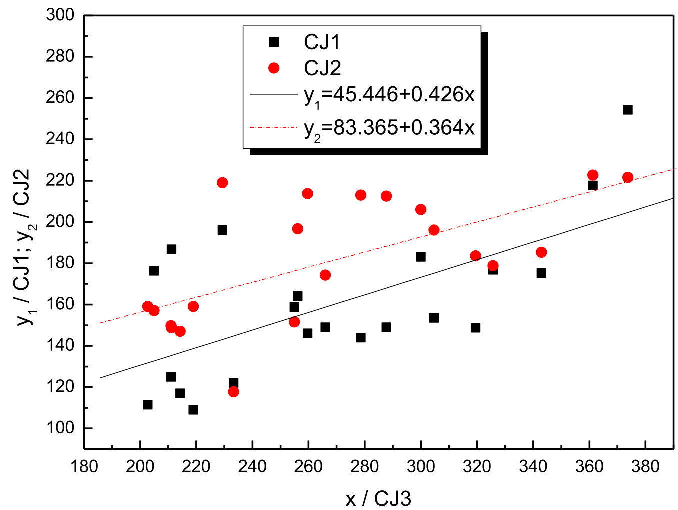

Fig. 9. Scatter diagram and regression lines of CJ1, CJ2 and CJ3.

These aspects were both used to examine the right arm's lateral lift. They represented linear and angular movement when measuring the shoulder's ROM.

In Fig. 10 the$y$ axis was range of motion of the right shoulder (RS6) and the x axis was vertical movement of the right elbow (RS1). By linear regression and variance analysis, the second variable was significantly positively associated with the first ($r = 0.722$, $p = 0.0002 < 0.001$).

3.1.4.2. Maximum vertical movement of the right elbow for lateral lift (RS2) and maximum vertical movement of right elbow for backwards extension (RS3). No significant correlation was found between RS2 and RS3. Therefore, one variable cannot be used to predict the other.

3.1.4.3. Maximum horizontal movement of the right elbow for adduction (RS4) and maximum horizontal movement of right elbow for abduction (RS5). The scatter plot of RS4 and RS5 is shown in Fig. 11. They are defined as the independent variable of x and the dependent variable of y, respectively. An effective functional relationship was obtained through linear regression and variance analysis between RS4 and RS5 ($p = 0.04 < 0.05$). Note that r was only 0.451.

3.1.5. Ergonomics indices of ROM of the hips

As seen in Fig. 12, movement of the right knee (RH1) and range of motion of right hip (RH2) tend to be linearly correlated. RH1 is denoted by x while RH2 by y ($r = 0.8626$, $p = 0.0001$).

As shown in Fig. 5d, movement of left elbow (RW1) and movement of right elbow (RW2) are the indices used to measure the left and right bending of the waist by VICON460. The scatter plot (Fig. 13) revealed a linear relationship between them. RW2, the independent variable of x, was linearly correlated with RW1 ($r = 0.764$, $p < 0.001$).

3.2. Statistical analysis on ergonomics indices of level 2

3.2.1. Target pointing (TP) and right elbow (RELB)

TP could be correlated with RE, due to the kinematic process of the elbow extending to place the hand in a position near the target to allow extension of the finger into a pointing position. Because

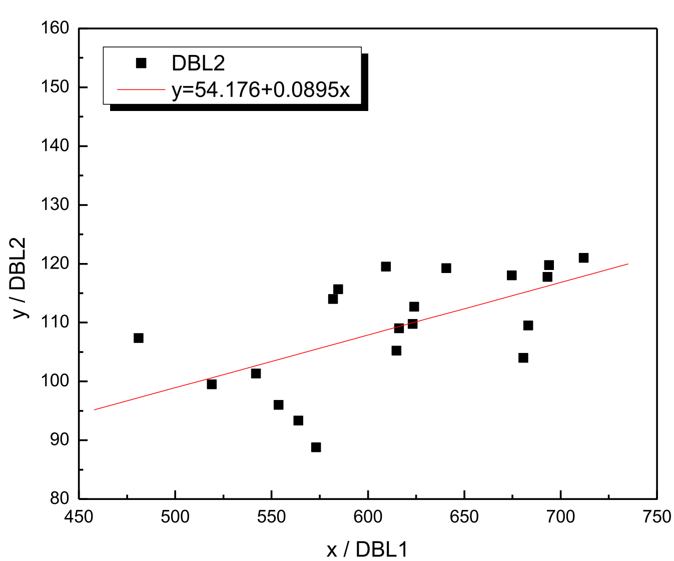

Fig. 8. Scatter diagram and regression lines of DBL1 and DBL2.

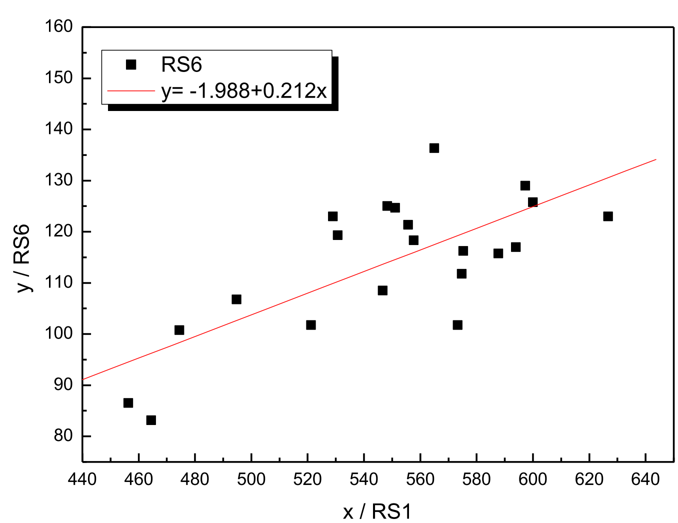

Fig. 10. Scatter diagram and regression line of RS1 and RS6.

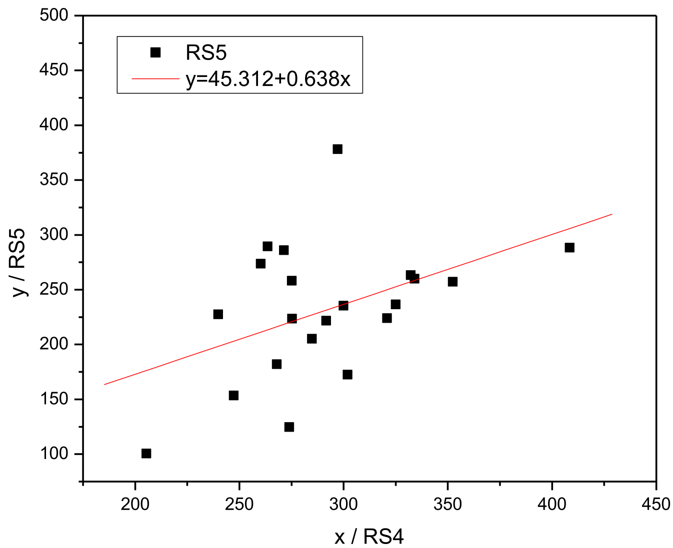

Fig. 11. Scatter plots and linear fitted line of RS4 and RS5.

the other indices of TP are linearly correlated to accomplishing of task time using the right arm with the B group for target pointing (TP3), we chose TP3 and the motion angle of the right elbow (RE1) from level 3 as the variables that represent TP and RE from level 2. Fig. 14 reveals that TP3 and RE1 are linearly correlated. We used x and y respectively to denote RE1 and 1/TP3. The regression coefficient was $r = 0.775$ and $p = 0.041 < 0.05$. The equation shows that any of the two variables can predict the other within the model.

3.2.2. *Pull down the veil (PDV) and maximum vertical movement of RELB for forward extension and maximum vertical movement of RELB for forward extension (RS)*

PDV involves a complex combination of various types of motions including the shoulder, elbow, and wrist. We hypothesized that PDV would be correlated with the right shoulder (RS) and right elbow (RE). However, regression analysis indicated that there was no significant relationship between PDV and RE, which may be partially explained by wrist movements and scapular orientation of the gleno-humeral joint.

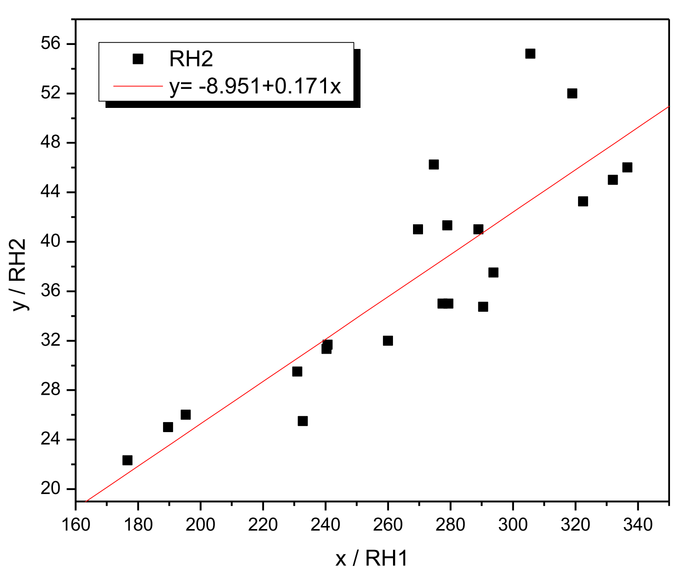

Fig. 12. Scatter diagram and regression line of RH1 and RH2.

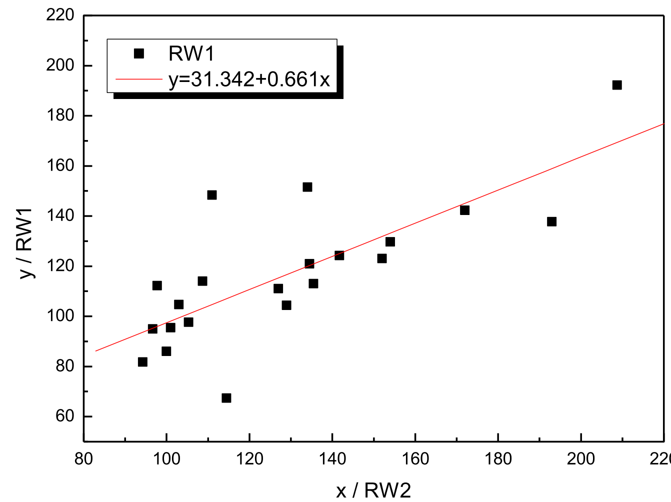

Fig. 13. Scatter diagram and regression line of RW1 and RW2.

The scatter plot of movement of the right wrist bar thumb side (PDV1) and maximum vertical movement for the right elbow for forward extension (RS2) (Fig. 15) shows that there is a linear relationship between them. The independent variable of x is RS2 and the dependent variable of y is PDV1. An effective regression model was developed using linear fitting, which showed that PDV1 and RS2 were significantly positively correlated ($r = 0.725$, $p = 0.0004 < 0.001$).

3.2.3. *Controlling of joysticks (CJ) and RS*

CJ3 (y) (Fig. 16) was positively correlated with maximum vertical movement of right wrist bar thumb side (RS1) (x) ($r = 0.647$, $p < 0.01$). Therefore, a predictive relationship exists between them.

3.3. *Statistical analysis of ergonomics indices of level 1*

The interrelation analysis on ergonomics indices of level 2 demonstrated that the range of motion and dexterity for tasks indices of level 1 are correlated with the ROM indices of level 1. Increased range of movement could lead to greater dexterity for successful completion of tasks. However, dexterity is a derived

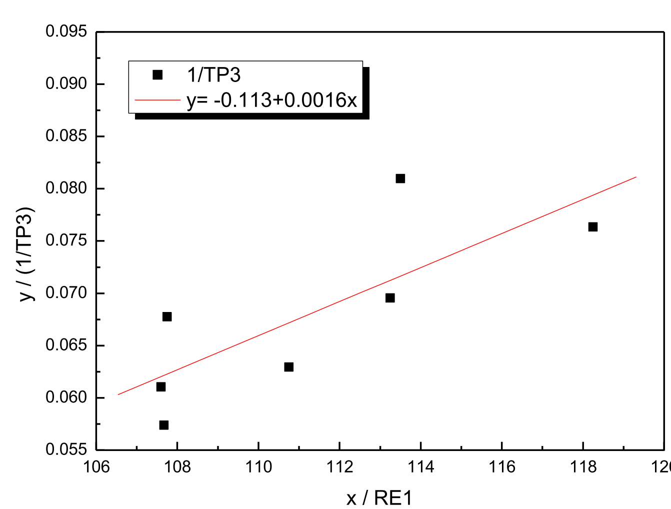

Fig. 14. Scatter diagram and regression line of RE1 and 1/TP3.

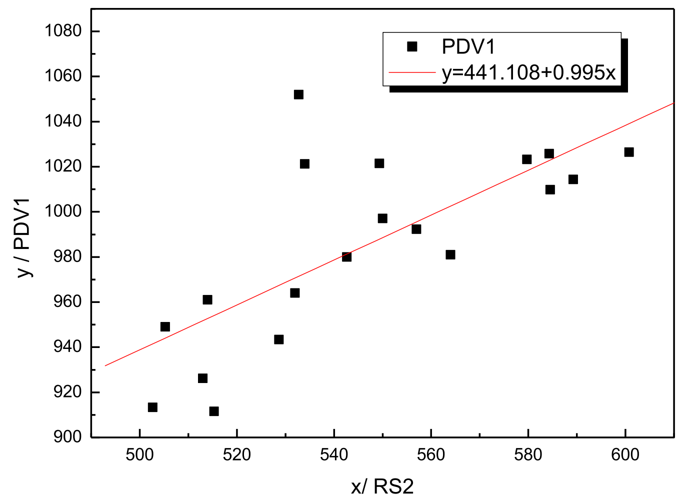

Fig. 15. Scatter diagram and regression line of RS2 and PDV1.

ergonomics factor that encompasses many elements, so it is impossible to describe it solely by ROM indices. Therefore, ergonomics indices in level 1 should be preserved.

3.4. Validation of the optimized ergonomics indices

To validate the optimized ergonomics indices, we used them in the ergonomics evaluation of pressurized partial pressure suits. Analysis of variance was used to test the effects of various pressures. It was concluded that a PPS had a significant impact on the pilot's range of motion (ROM) and dexterity but no significant effect on his or her grip strength. Range of motion and dexterity decreased as pressure increased, but they were not affected to the same extent. These results were highly similar with the results from ergonomics indices before optimization, hence the optimized ergonomics indices were validated.

4. Discussion

The following is a summary of the objectives of this study: (1) to discuss and develop the functional relationships between ergonomics indices, (2) to determine the predictive models among ergonomics indices, and (3) to optimize and validate the ergonomics indices system. As expected, there are some significant interrelationships between the ergonomics indices of PPS (Table 4). Moreover, the equations obtained were able to serve as predictive models; thus some indices can be obtained from the models and need not be derived through experiments.

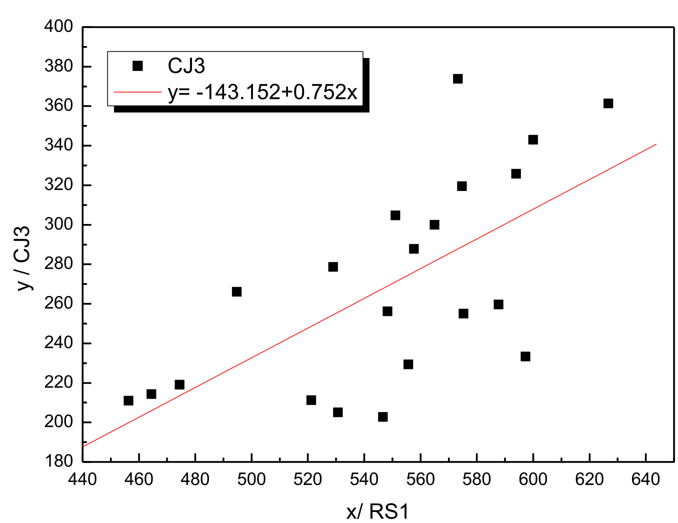

Fig. 16. Scatter diagram and regression line of RS1 and CJ3.

We will now consider the relationship of the 23 indices within level 3. Nine pairs of effective linear equations were derived (Table 4). Between accomplished time of task using the right arm with B group for target pointing (TP1), accomplished time of task using left arm with BS group for target pointing (TP2), accomplished time of task using right arm with BS group for target pointing (TP3) and inverse orientation accomplished time of task using right arm with BS group for target pointing (TP4) two pairs of suitable equations were obtained. These findings demonstrate that TP3 can act as a predictor for TP2 and TP4. Moreover, TP2 and TP4 were positively correlated with TP3. The slope was 0.960, and the intercept −0.352. These results indicated that TP3 is almost identical to TP4. Therefore, we concluded that subjects were just as capable of completing the target pointing task with their left arm as their right. Therefore, under restricted experimental conditions, for example, lack of time to study both arms, it is sufficient to only measure TP3. The predicted model for TP3 can affectively predict TP2 and TP4. However, TP1 is a simpler manipulation task than TP3. Moreover, TP3 is also more comparable to the tasks that must be accomplished during an actual flight. Thus, a conclusion can be drawn that TP3 is a preferable ergonomics index to examine target pointing than TP1.

Flexion angle of the right knee for drawing back a leg (DBL1) and movement of right ankle to draw back a leg (DBL2) are two indices used to assess the same operational task. Our statistical results confirmed that they are interchangeable terms of the descriptive linear equation. In addition, our prior study (Hu et al., 2008a,b) concluded that DBL1 was more sensitive to PPS than DBL2; thus we can conclude that DBL1 is a better ergonomics index than DBL2.

CJ1, CJ2 and CJ3 were adopted to examine three different tasks of CJ. Each motion should have different effects on the ability to accomplish tasks. Thus, it was initially considered that these three indices were not correlated with each other. However, significant relationships were found between them. The reason might be the integration of all motions. These findings imply that measuring only one variable is sufficient and the predictive models can determine the other two. It was found from these experiments that accomplishment of CJ3 is more exact and uniform when compared to the other two indices; thus, CJ3 is the optimal element that reflects the ergonomics characteristics of CJ more objectively than the other two.

Table 3 shows that maximum vertical movement for drawing back a leg (RS1) and maximum motion of the right shoulder in the

Table 4
The relationships between the ergonomics indices of PPSs.

Ergonomics indices	*y*	*x*	*a*	*b*	*R*	*p*
Level 3	TP2	TP3	3.267	0.782	0.894	<0.01
	TP4	TP3	0.352	0.960	0.992	<0.0001
	DBL2	DBL1	54.176	0.0895	0.5999	<0.01
	CJ1	CJ3	45.446	0.426	0.634	<0.005
	CJ2	CJ3	83.365	0.364	0.639	<0.005
	RS6	RS1	−1.988	0.212	0.722	<0.001
	RS5	RS4	45.321	0.638	0.451	<0.05
	RH2	RH1	−8.951	0.171	0.8626	<0.0001
	RW1	RW2	31.342	0.661	0.764	<0.0001
Level 2	1/TP	RE	−0.113	0.0016	0.775	<0.05
	PDV	RS	441.108	0.995	0.725	<0.001
	CJ	RS	−143.152	0.752	0.647	<0.01

coronal plane (RS6) are linearly correlated. In order to unify dimensions, RS1, which is in agreement with the other indices of RS, measured in mm, was selected as the preferred index from RS1 and RS6. Though RS4 and RS5 are also linearly correlated, their regression coefficient is only 0.451. Therefore, RS4 and RS5 must both be measured at the same time.

Similar to the principle of determining DBL1 as the optimal ergonomics index, RH2 is the optimal index between RH1 and RH2.

As RW1 and RW2 are also linearly correlated, the two indices can be used to replace one another in the predictive model of $RW1 = 31.342 + 0.661RW2$. Human kinematic characteristics suggest that right oriented body motions are more easily executed than left oriented motions for right handed people. Accordingly, when performing the tasks, right oriented motions are preferable to left oriented motions. Our previous investigations showed that RW2 was slightly more sensitive to a PPS than RW1. The performance of RW1 and RW2 were reduced by 16% and 18% with a PPS, respectively. Based on the above, RW2 was chosen as the better ergonomics index for RW1 and RW2.

Subsequently, correlations between ergonomics indices in level 2 were also studied. Three pairs of effective linear equations were developed (Table 4). These three pairs of functional relations suggest that dexterity and operational reach, which belong to the ergonomics indices of level 1, are linearly correlated. However, dexterity and operational reach cannot predict one another because not all of their ergonomics indices are linearly correlated.

The optimized ergonomics index system was validated by applying it to the study of PPSs' ergonomics performance under six different pressure conditions.

The optimal ergonomics evaluation index system developed is shown in Table 5. We can use the index system to evaluate the effects of PPS with fewer experiments in less time.

5. Conclusions

The present study investigated the relationships between 36 ergonomics indices used to evaluate the effects of personal protective suits. The results showed that 12 pairs of ergonomics indices were linearly correlated. Based on these effective functional relationships an optimal ergonomics evaluation index system of PPSs was proposed (Table 5). However, some caution needs to be exercised in interpreting the results because when evaluating a PPS, the pressurization time must be limited to ensure the safety of the participant, and this time is too short to measure all the indices before optimization. Consequently, not all indices can be fully tested in this situation. The proposed optimal index system reduces the number of indices that must be measured under a variety of test conditions. By establishing the functional relationships among these ergonomics indices and determining redundant measures, the proposed optimal index system also significantly reduces the difficulties of appraising the performance of PPSs. Use of the proposed index system can improve the ergonomics design and evaluation of PPSs.

Table 5
The optimal ergonomics evaluation index system for PPSs.

Optimal ergonomics indices of level 1	Optimal ergonomics indices of level 2	Optimal ergonomics indices of level 3
Manipulation missions	Target pointing	TP3
	Pull down the veil	PDV1
	Drawing-back the legs	DBL1
	Control of the joystick	CJ3
Operational reach	ROM of shoulder joint	RS1
		RS2
		RS3
		RS4
		RS5
	ROM of elbow joint	RE1
	ROM of hip joint	RH2
	ROM of waist joint	RW2
	ROM of knee joint	RK1
Operational strength	Grip strength	GS1

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Appendix. Definitions of the 39 Markers

Markers	Definition	Position
LFHD	Left front head	Left temple
RFHD	Right front head	Right temple
LBHD	Left back head	Left back of head
RBHD	Right back head	Right back head
C7	Seventh cervical vertebrae	Base of the neck
T10	Tenth thoracic vertebrae	Center mid-back
CLAV	Clavicle	Top of the breast bone
STRN	Sternum	Base of the breast bone
RBAC	Right back	Center of the right shoulder blade
LSHO	Left shoulder	Placed on the bony prominence on top of the left shoulder
LUPA	Left upper arm	Placed on the outside of the upper arm
LELB	Left elbow	Placed on the bony prominence on the outside of the elbow joint
LFRM	Left forearm	Placed on the outside of the lower arm
LWRA	Left wrist	Extended from the thumb side using a wrist bar
LWRB	Left wrist	Extended from the little finger side using a wrist bar
LFIN	Left finger	Placed just below the middle knuckle on the left hand
RSHO	Right shoulder	Placed on the bony prominence on top of the right shoulder
RUPA	Right upper arm	Placed on the outside of the upper arm
RELB	Right elbow	Placed on the bony prominence on the outside of the elbow join
RFRM	Right forearm	Placed on the outside of the lower arm
RWRA	Right wrist bar thumb side	Extended from the thumb side using a wrist bar
RWRB	Right wrist bar pinkie side	Extended from the little finger side using a wrist bar
RFIN	Right finger	Placed just below the middle knuckle on the right hand
LFWT	Left front waist	Left front waist
RFWT	Right front waist	Right front waist
LBWT	Left back waist	Left back waist
RBWT	Right back waist	Right back waist
LTHI	Left thigh	Placed on the outside of the thigh below hand swing
LKNE	Left knee	Placed on the outside of the knee joint
LSHN	Left shin	Placed on the outside of the lower leg
LANK	Left ankle	Placed on the bony prominence on the outside of the ankle
LHEE	Left heel	Placed on the back of the foot
LTOE	Left toe	Placed on the tip of the big toe
RTHI	Right thigh	Placed on the outside of the thigh below hand swing
RKNE	Right knee	Placed on the outside of the knee joint

(*continued*)

Markers	Definition	Position
RSHN	Right shin	Placed on the outside of the lower leg
RANK	Right ankle	Placed on the bony prominence on the outside of the ankle
RHEE	Right heel	Placed on the back of the foot
RTOE	Right toe	Placed on the tip of the big toe

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An experimental study on the ergonomics indices of partial pressure suits☆

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A B S T R A C T

Partial pressure suits (PPSs) are used under high altitude, low-pressure conditions to protect the pilots. However, the suit often limits pilot's mobility and work efficiency. The lack of ergonomic data on the effects of PPSs on mobility and performance creates difficulties for human factor engineers and cockpit layout specialists. This study investigated the effects of PPSs on different ergonomic mobility and performance indices in order to evaluate the suit's impact on pilot's body mobility and work efficiency. Three types of ergonomics indices were studied: the manipulative mission, operational reach and operational strength. Research results indicated that a PPS significantly affects the mobility and operational performance of the wearers. The results may provide mission planners and human factors engineers with better insight into the understanding of pilots' operational function, mobility and strength capabilities when wearing PPS.

1. Introduction

Flying high-performance fighters like supersonic cruise and super-agility airplanes has created greater demands on the protective capacities of a partial pressure suit (PPS), which leads to an increasing conflict between its function and efficiency (Færevik and Eidsmo Reinertsen, 2003; Murray et al., 2011; Rudnjanin et al., 2006). The integration of protective functions, such as compensation, anti-gravity, anti-penetration and cold-resistance intensifies, may affect the impact of a PPS on pilot's efficiency (Albery and Chelette, 1998; Alexander and Laubach, 1973; Zhang, 1999). Therefore, ergonomics research on PPSs has been focused on effectively ensuring the efficiency of a PPS without reducing its protective capacities.

So far there have been only a few ergonomics studies on PPSs, and no ergonomic evaluation index system has been developed. However, a PPS is only one kind of protective suit and thus the study of PPSs can also use the experiences developed for other types of protective suits for reference (Abramov et al., 2005; Aghazadeh and Rajulu, 2006; Chang et al., 2007; Havenith and Heus, 2004; Huck, 1988; Liu et al., 1998; O'Hearn et al., 2005; White et al., 1994). Ergonomics research on protective suits can be divided into three main categories: subjective investigation, objective testing and numerical simulation. Among them, subjective investigation is the most traditional. It is carried out by analysing questionnaires and the subjective reflections of the subjects. White et al. (1994) studied the influence of U.S. Air Force Advanced Technology Anti-G Suits (ATAGS) and U.S. Navy Enhanced Anti-G Lower Ensembles (EAGLE) on pilots' operating performance by questionnaire. Based on the results, they improved the functions of the protective suit. Subjective investigation is easy to carry out, but is subject to both subject and contextual bias, which makes the data less precise. With the development of technology, ergonomic studies of protective suits have transformed from qualitative analysis to quantitative studies. Objective ergonomics research falls into two categories: human mechanics (flexibility, power, etc.) and manipulation performance. Adams and Keyserling (1993) and Coca et al. (2008) studied the effect of protective suits on the flexibility of wearers by using a goniometer and a flexometer to collect data on range of motion. However, the precision of this method can be influenced by the variability of operators collecting the data. O'Hearn et al. (2005) analysed the impact of Army cold winter clothing on soldiers' agility and gait characteristics by applying a three-dimensional video-based motion capture system, which can record human moving trajectory and achieve data on range of motion and gait characteristics. Albery and Chelette (1998) designed an experiment in which subjects tracked a simulated "bogey" aircraft on a visual

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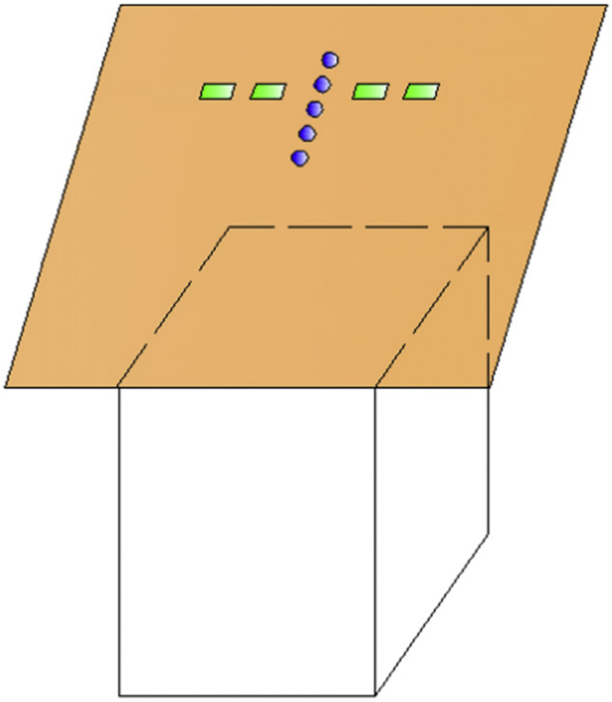

Fig. 1. Target-pointing board.

display and performed a secondary task to test the effect of G suit type on cognitive performance and found that more advanced protective systems not only allowed longer G endurance, but provided adequate support for maintained cognitive performance throughout the extended exposure. Moreover, advances in computer technology have enabled numerical simulation to be used in ergonomics studies of protective suits. This method studies the ergonomics of protective suit by using a digital human model and a personal protective equipment model. Kozycki (1998) and Kozycki and Gordon (2002) developed a modelling and simulation approach to examine the encumbrance of helicopter aircrew clothing and equipment. He compared the results of the simulation with that of a three-dimensional motion capture system and proved the feasibility of his numerical simulation method. However, this method is a work in progress and needs to be improved. Although there have been many investigations on the ergonomics of protective suits, systemic ergonomics evaluations and indices system of protective suits, considering body mechanics, the vehicle and the environment, has not been studied so far.

The aim of this study was to develop an ergonomics evaluation and indices system for PPSs based on the analysis of pilot motion range, operational performance and operational strength. The research on range of motion, including joints' moving angles, accessible domain, etc. while pilots were performing various operating tasks, was measured by a three-dimensional video-based motion capture system. Operational performance was judged by performance of specific flight tasks. Operational strength was assessed by measuring the power provided by the hands and feet. Based on the results, this work established a system for evaluating PPSs ergonomic design and for testing improvements. It also provides a reference for mission planning and the man-machine interface design of airplane cockpits.

2. Methods

2.1. Subjects

A total of twenty-one Chinese male undergraduate students with an average age of 23.14 years (range 21–25) were enrolled in this study. The average height and weight were 169.48 cm (range 165–175 cm) and 62.52 kg (range 56–77 kg) respectively. The subjects were all right-hand dominant and were chosen carefully to ensure that their body-sizes met the requirements of a PPS (Hu et al., 2008). All subjects had knowledge of PPSs and flight missions. Their physical condition met the experimental requirements, including no physical disability or limitations and no case histories of heart and lung problems. They were also informed beforehand of the purpose of the study, the nature of the test conditions, the experimental procedures, and the risks associated with the study. Before testing, all subjects were trained to a given criterion of performance and to be familiar with the experimental tasks.

2.2. Apparatus

The apparatus used in this study included a three-dimensional video-based motion capture system, a target-pointing board, a hand dynamometer, and a step-tread apparatus. The three-dimensional video-based motion capture system (VICON460) is composed of six video cameras with a sampling frequency of 120 Hz, and corresponding accessories. This system was used to

Fig. 2. Step-tread apparatus.

measure the range of motion (ROM) for various body segments. Fig. 1 shows the rectangle target-pointing board used in this study to measure performance of the target-pointing task. A grip strength dynamometer (WCS-100II) provided instantaneous strength readings from 0 to 100 ± 0.1 kg. The step-tread apparatus (Fig. 2) was specially designed to test the step-tread strength of pedalling an aircraft rudder and the readings ranged from 0 to 60 ± 0.01 kg.

3. Study design

3.1. Clothing conditions

Two different clothing conditions, conventional clothing (CC) condition and the partial pressure suit (PPS) condition, were used in this study. The CC condition consisted of casual attire (short pants and vest) while the PPS condition used in this study was a capstan anti-G and counter pressure suit which is widely used by the pilots (Fig. 3).

3.2. Ergonomics indices and test variables

The seated capabilities of the subjects were assessed using three types of ergonomics indices (Table 1). The ergonomics indices that were chosen were based on the actual manipulative and reach activities of a pilot during flight, and they can provide useful information to the cockpit designers on functional reach distances and performance capabilities. Each ergonomic index contained several different test variables with corresponding test measures, for example, ergonomic measures of manipulative ability were used to examine the operational capability of wearers. The test measures were designed based on actual flight task requirements. For example, the drawing back the legs task was designed to measure the performance of ejection survival actions. The other two types of ergonomics indices were used to measure the operational reach and operational strength of the wearers.

Fig. 3. Partial pressure suit.

Table 1
Ergonomics indices and test variables.

Ergonomics indices	Test indices	Variables (abbreviation)
Manipulative missions	Target pointing	Accomplishing time of task (AT)
	Adjusting the helmet	Displacement of RWRB (D_{RWRB})
	Drawing-back the legs	Motion angle of RKNE joint (Ang_{RKNE})
		Displacement of RANK (D_{RANK})
	Control of the joystick	Displacement of RWRA (D_{RWRA})
Operational reach	ROM of shoulder joint	Motion angle of RSHO joint (Ang_{RSHO})
		Displacement of RELB (D_{RELB})
	ROM of elbow joint	Maximal flex/extension angle (Ang_{RELB})
	ROM of hip joint	Displacement of RKNE (D_{RKNE})
		Maximal motion angle (Ang_{Hip})
	ROM of waist joint	Displacement of LELB (D_{LELB})
		Displacement of RELB (D_{RELB})
Operational strength	Grip strength	Maximal grip strength (Max_{GS})
	Step-tread strength	Maximal step-tread strength (Max_{STS})

3.3. Description of test indices and variables

The test indices and variables and their units are shown in Table 2, and are described in detail as follows.

Table 2
Description and codes of all test variables.

Test indices	Variables	Descriptions of variables (codes)
Manipulative missions		
Target pointing	AT_{B-R} (s)	AT of right arm for button(B) group (*TP1*)
	AT_{BS-L} (s)	AT of left arm for button and switch(BS) group (*TP2*)
	AT_{BS-R} (s)	AT of right arm for BS group (*TP3*)
	$AT_{RE-BS-R}$ (s)	Reverse orientation AT of right arm for BS group (*TP4*)
Adjusting the helmet	D_{RWRB} (mm)	Displacement of RWRB (*PDV1*)
Drawing-back the legs	Ang_{RKNE} (deg)	Flexion angle of right knee joint (*DBL1*)
	D_{RANK} (mm)	Displacement of right Rank (*DBL2*)
Control of the joystick	D_{F-RWRA} (mm)	Pushing forward displacements of RWRA (*CJ1*)
	D_{L-RWRA} (mm)	Pushing left displacements of RWRA (*CJ2*)
	D_{R-RWRA} (mm)	Pushing right displacements of RWRA (*CJ3*)
Operational reach		
ROM of shoulder joint	$D_{LL-RELB}$ (mm)	Maximal vertical displacement of RELB for lateral lift (*RS1*)
	$D_{FE-RELB}$ (mm)	Maximal vertical displacement of RELB for forward extension (*RS2*)
	$D_{BE-RELB}$ (mm)	Maximal vertical displacement of RELB for backward extension (*RS3*)
	$D_{AD-RELB}$ (mm)	Maximal horizontal displacement of RELB for adduction (*RS4*)
	$D_{AB-RELB}$ (mm)	Maximal horizontal displacement of RELB for abduction (*RS5*)
	Ang_{RSHO} (deg)	Maximal motion angle of shoulder joint in the coronal plane (*RS6*)
ROM of elbow joint	Ang_{RELB} (deg)	Motion angel of elbow joint (*RE1*)
ROM of hip joint	D_{RKNE} (mm)	The displacement of RKNE (*RH1*)
	Ang_{Hip} (deg)	Maximal motion angel of right hip joint (*RH2*)
ROM of waist joint	D_{LELB} (mm)	Displacement of LELB (*RW1*)
	D_{RELB} (mm)	Displacement of RELB (*RW2*)
Operational strength		
Grip strength	Max_{GS} (kg)	Maximal grip strength (*GS1*)
Step-tread strength	$Max_{ST\ S}$ (kg)	Maximal step-tread strength (*STS1*)

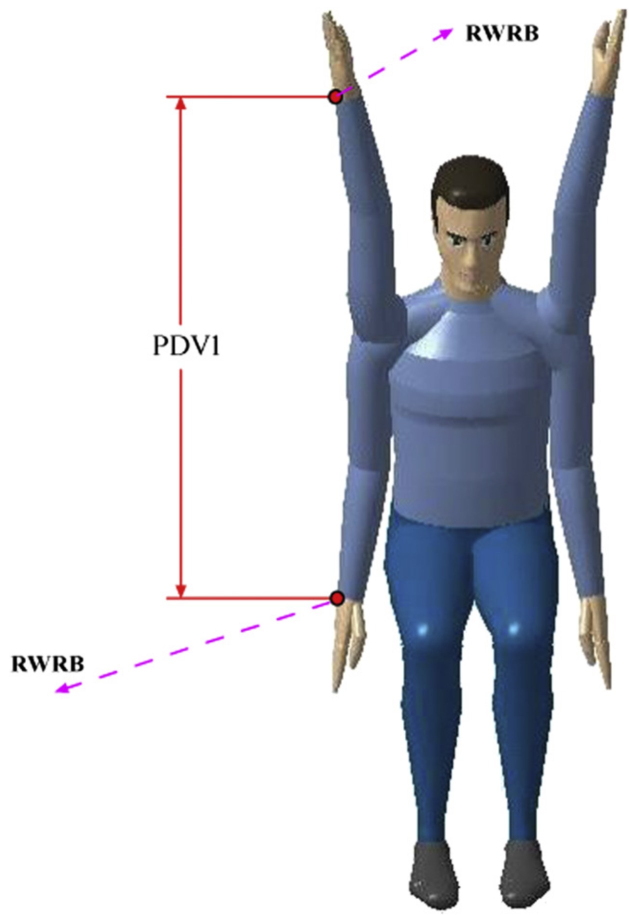

Fig. 4. The test variable of adjusting the helmet.

3.3.1. Manipulative missions

3.3.1.1. Target pointing. Two group tests were completed in this study in order to investigate the effects of PPSs on tasks with different levels of complexity. These two groups were: five buttons group (B group) and five buttons with four switches group (BS group), respectively. Tests for the BS group included tests of the left and right arm flexion and right arm extension, while the B group only included right arm flexion and extension. The test required the subject to sit in front of a target-pointing board with his arm on an armrest. The subject was required to maintain his trunk upright. After a start signal, the subject outstretched his arm to press down targets as quickly as possible, and then pulled back his arm to the initial position. Such actions were repeated five times and the subject was asked to not only touch the targets but also press down the buttons or correctly control the switches. This test was designed based on the panel operations task. The time required to accomplish all tasks was defined as the accomplishing time of the task (AT). *TP1*, *TP2*, *TP3* and *TP4* were described in Table 2.

3.3.1.2. Adjusting the helmet. During the ejection survival actions, the pilot should adjust his helmet firstly. In this experiment the subject was asked to raise both arms as high as possible and then pull them down until the flexion angle of his elbow joint came to its limit. The test variable, defined as *PDV1*, was the maximal displacement of right wrist bar little finger side (RWRB) (Fig. 4).

3.3.1.3. Drawing-back the legs. This task was designed to measure the peak leg extension required to reach the rudder pedals and to determine if the PPS impeded the ability to pull the legs close to the seat when preparing for ejection. Both legs were first placed in a standard position where the relative angle of thigh and shank was 90°. Then the subject tried his best to outstretch both legs then draw them back till the knee joints reached their maximal flexion angle. Two test variables, defined as *DBL1* and *DBL2*, are shown in Fig. 5.

3.3.1.4. Control of the joystick. While sitting upright, the subject was asked to operate the joystick in a sequence, pushing it forward, then left, then right. Fig. 6 displays the three test variables: *CJ1* (pushing forward displacement of right wrist bar thumb side (RWRA)), *CJ2* (pushing left displacement of RWRA), *CJ3* (pushing right displacement of RWRA).

3.3.2. Operational reach

3.3.2.1. ROM of shoulder joint. Measurements of the range of motion index included right arm lateral lift, fore/aft extension and adduction/abduction. While doing these actions, the subject moved his arm in the specified plane without rotation. The six test variables are shown in Fig. 7 and are described in Table 2 as *RS1*, *RS2*, *RS3*, *RS4*, *RS5*, and *RS6*.

3.3.2.2. ROM of elbow joint. Keeping the upper arm pointing down, the subject was asked to bend his forearm until the elbow joint reached its maximal flexion angle. Fig. 8 gives the definition of the test variable which is described as *RE1* in Table 2.

3.3.2.3. ROM of hip joint. The subject raised his right leg as high as possible. Fig. 9 illustrates the two test variables *RH1* and *RH2* which are described in Table 2.

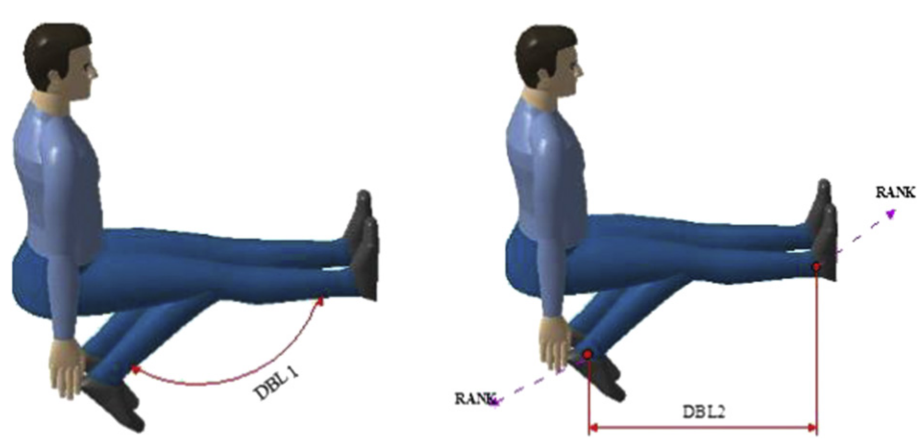

Fig. 5. Test variables of drawing-back the legs.

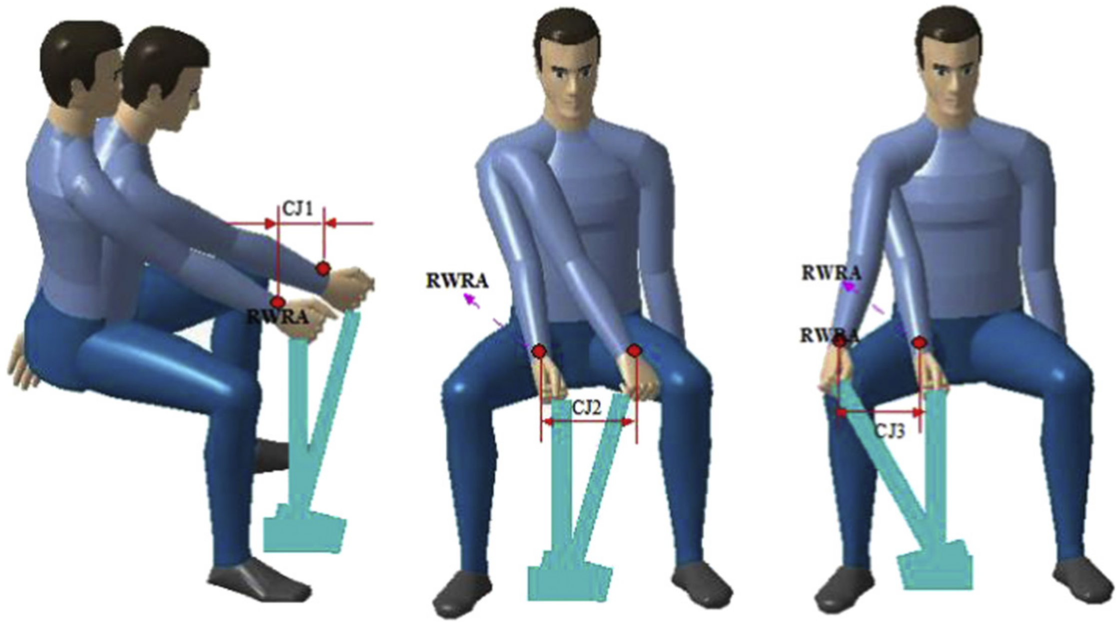

Fig. 6. Test variables of control of the joystick.

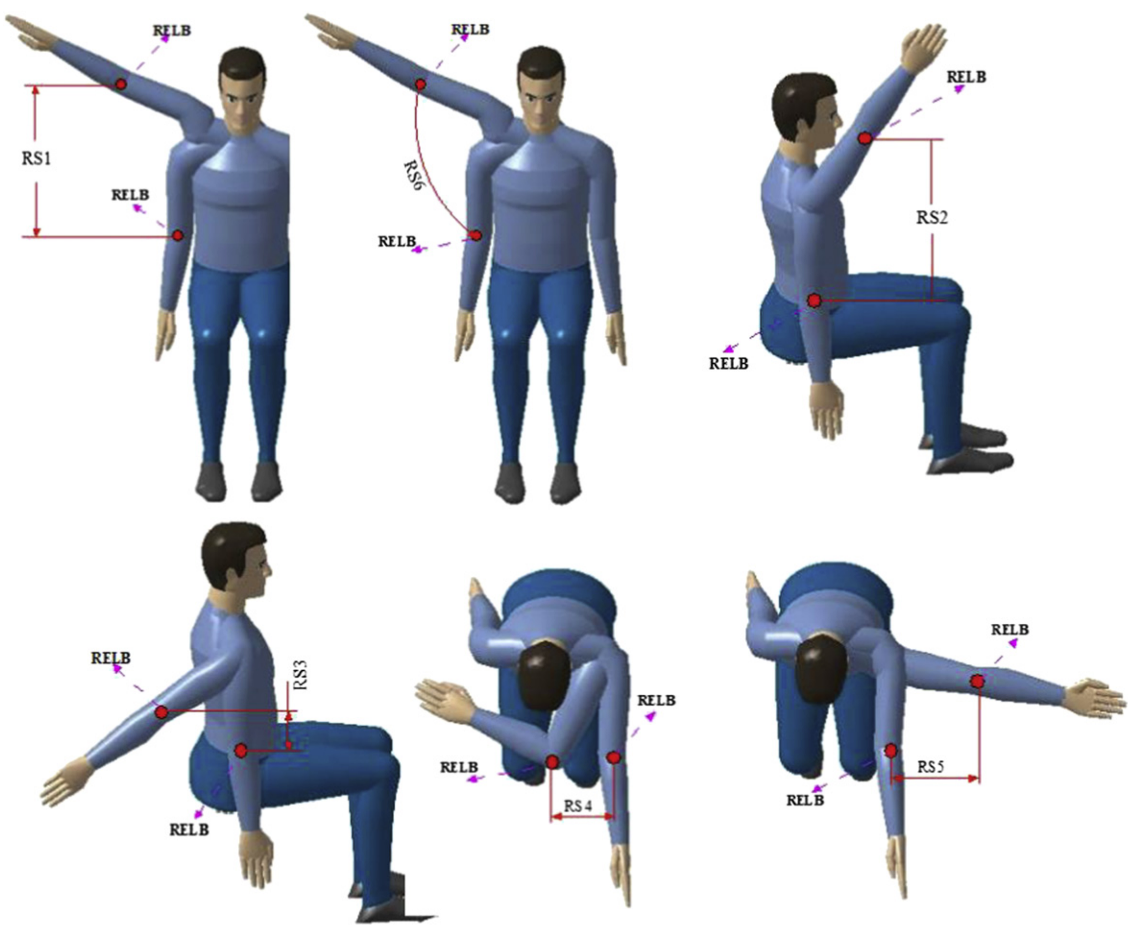

Fig. 7. Test variables for ROM of shoulder joint.

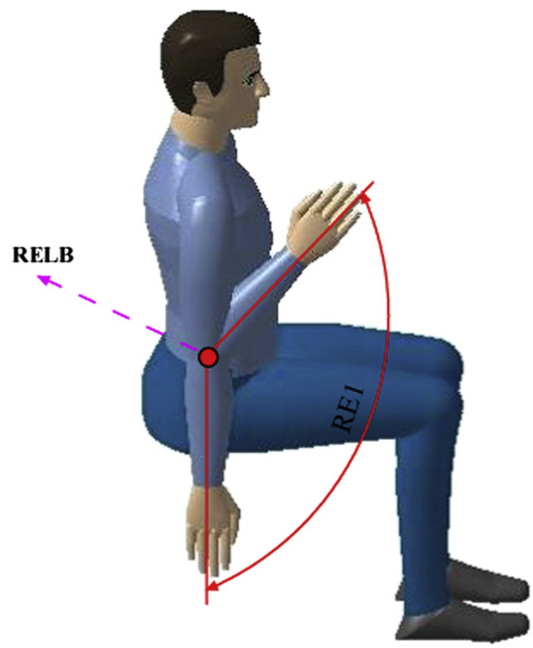

Fig. 8. The test variable for ROM of elbow joint.

3.3.2.4. ROM of waist joint. Starting from a straight sitting position, the subject bent his waist laterally to the left and then right as far as possible without twisting. Test variables *RW1* and *RW2* are illustrated in Fig. 10 and are described in Table 2.

3.3.3. Operational strength

3.3.3.1. Grip strength. While sitting with the trunk erect, the subject outstretched his right hand and grasped the hand dynamometer as firmly as he could (Fig. 11). The test variable was maximal grip strength *GS1*.

3.3.3.2. Step-tread strength. Keeping the upper trunk upright, the subject extended his right leg to step on the tread sensor (Fig. 12). Here the test variable was the maximum step-tread strength *STS1*.

3.4. Data process and statistical analysis

The collected data were examined for outliers to exclude any questionable data before they were analyzed. The final number of subjects used for statistical analysis for each test varied between 17 and 21 and this is shown in Table 3. The data for the analysis were the average of each subject's repeated trials for a given activity under each clothing condition. Statistical analysis was accomplished by a multivariate software package (SPSS v19) with a significance level at $p < 0.05$ throughout. The results of CC and PPS trials were compared using a paired *t* test.

4. Procedure

All experiments were conducted in the Man-Machine-Environment System laboratory at Beihang University. Every subject completed tests under two clothing condition (CC, PPS) with enough time in between to rest. The subject sat in the center of the motion capture area with his trunk upright. The anthropometric parameters of the subject were measured prior to the experiment for choosing the appropriate PPS size. After donning a PPS, the subject maintained the required seating posture throughout. Then a trained and qualified laboratory assistant adjusted the PPS for the subject so that it properly fit him. Finally, 39 reflective markers were attached to the subject, each corresponding to an anatomical landmark (Fig. 13 and Appendix). Fig. 13 shows the marker positions for a whole body capture. Formal tests were carried out after all these preparations. The order of wearing the suits was counterbalanced.

5. Result and discussion

Table 3 shows the comparisons between the CC and PPS tests for each variable. Results are summarized below for the manipulative mission, operational reach, and operational strength tasks separately.

5.1. Manipulative missions

The effects of a PPS on the four indices of manipulative missions showed that each test variable was significantly different between the two conditions.

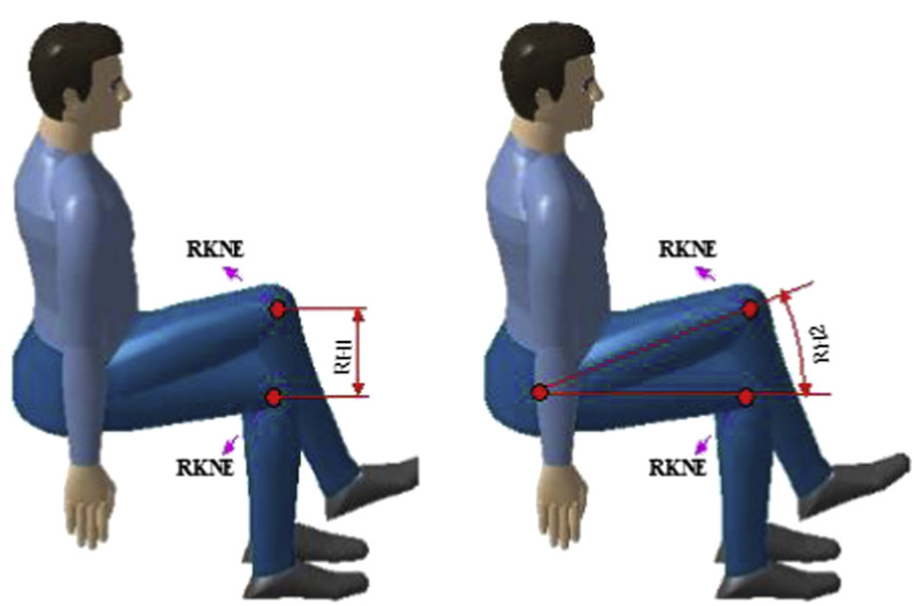

Fig. 9. Test variables for ROM of hip joint.

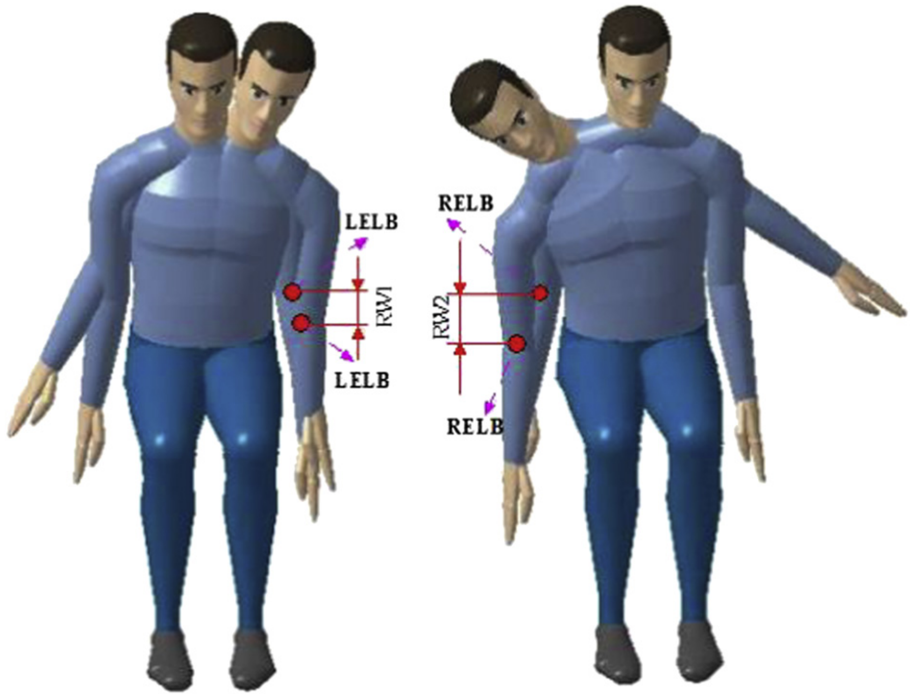

Fig. 10. Test variables for ROM of waist joint.

5.1.1. *Target-pointing*

A PPS significantly influences target pointing, as can be seen from the substantial changes in the four test variables in Table 3 ($p < 0.01$).The AT in the PPS condition is longer than that in the CC condition, indicating that wearing a PPS increases the operational difficulty of the target-pointing task. It was also found that wearing a PPS resulted in a 5% increase in *TP1*, 10% in *TP2*, 8% in *TP3*, and 8% in *TP4*.

5.1.2. *Adjusting the helmet*

Comparisons of the two variables for adjusting the helmet in both the CC and PPS conditions are listed in Table 3. The results indicated that a PPS had significant negative effects on the action of adjusting the helmet ($p < 0.001$), decreasing *PDV1* by 8%.

5.1.3. *Drawing-back the legs*

Two test variables were used to analyze the effects of a PPS on the performance of drawing-back legs. The comparison results exhibited significant differences in both *DBL1* and *DBL2* ($p < 0.001$). The effects of these two variables were a 13% and 3% decrease, respectively.

5.1.4. *Control of the joystick*

Compared with the adjusting the helmet and drawing back the legs tests, a PPS significantly decreased the performance of controlling the joystick ($p < 0.001$). The changes to *CJ1*, *CJ2*, and *CJ3* were 14%, 18%, and 10%, respectively.

5.1.5. *Discussion*

As seen from the statistical analysis results (Fig. 14), the increase of *TP1* is less than that of *TP3* showing that the target-pointing task for buttons and switches was more affected by the PPS than only buttons. Thus, it can be concluded that the impairment effect of a PPS will be greater if the operation missions are more complicated.

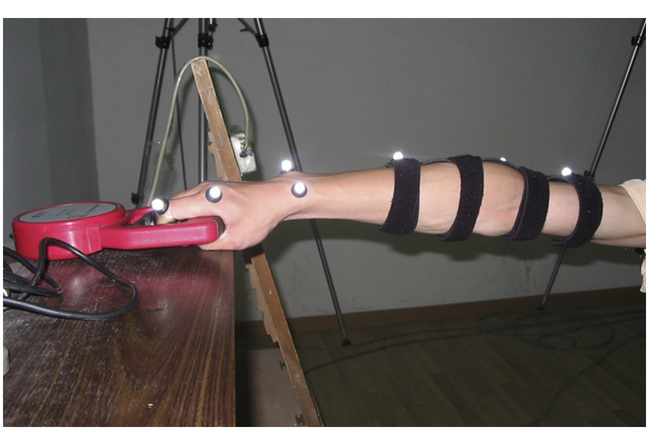

Fig. 11. Grip strength.

Fig. 12. Step-tread strength.

Table 3
Mean comparisons results of test variables.

Variables codes	Subjects (n)	Clothing condition	
		CC◆	PPS
Manipulative missions(s)			
TP1	10	6.83 ± 1.45	7.20 ± 1.68
TP2	7	13.55 ± 1.39	14.92 ± 1.58** above
TP3	7	13.77 ± 1.97	14.90 ± 1.81**
TP4	7	12.96 ± 2.06	13.95 ± 1.75**
PDV1	20	1069.13 ± 40.37	972.76 ± 50.69
DBL1	20	125.80 ± 15.46	109.07 ± 9.54***
DBL2	20	645.10 ± 61.63	624.25 ± 56.96***
CJ1	20	186.00 ± 42.64	160.50 ± 36.87***
CJ2	21	223.69 ± 32.75	182.51 ± 28.69***
CJ3	21	299.70 ± 49.27	270.55 ± 53.66***
Operational reach(mm)			
RS1	21	612.62 ± 33.33	548.78 ± 46.14***
RS2	19	600.62 ± 33.33	549.63 ± 32.47***
RS3	19	163.58 ± 50.96	145.90 ± 49.74**
RS4	21	330.51 ± 45.26	291.85 ± 43.98***
RS5	21	277.65 ± 68.59	231.50 ± 62.25***
RS6	21	134.72 ± 9.51	114.89 ± 14.64***
RE1	21	117.40 ± 5.44	107.82 ± 6.25***
RH1	21	323.73 ± 43.65	268.36 ± 45.70***
RH2	21	49.79 ± 7.30	36.98 ± 9.07***
RW1	21	139.06 ± 32.13	116.79 ± 27.89***
RW2	21	157.69 ± 36.05	129.42 ± 32.14***
Operational strength(kg)			
GS1	19	42.89 ± 5.40	41.26 ± 5.35**
STS1	19	23.72 ± 2.90	23.56 ± 3.47

The data are described in the form of Average and SD ($\bar{x} \pm s$).
Compared with the control group (◆), ** $p < 0.01$, *** $p < 0.001$.

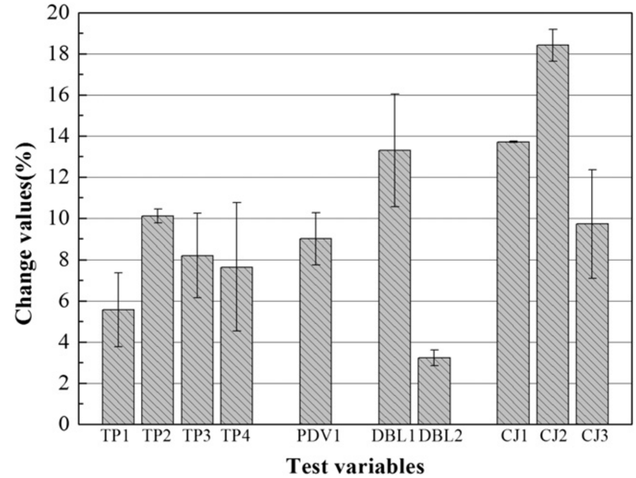

Fig. 14. Change values between CC and PPS for the test variables of manipulative missions.

Similarly, operational performance of the left arm was affected more severely by a PPS than that of the right arm. However, the decreases in performance of the two target-pointing tasks, *TP3* and *TP4* were the same. The results show that the decrease in target-pointing performance is due to the PPS restricting the wearers' mobility.

Fig. 15 shows that the mean values for controlling the joystick changed greatly for the four ergonomics indices when a PPS was worn, while the differences in the mean values between the CC and PPS for the other three indices (*CJ1*, *CJ2* and *CJ3*) were almost equal. The reduction in the operational capabilities of target pointing, adjusting the helmet and controlling the joystick indicated that a PPS significantly restricts the ROM of shoulder and elbow joints. The ROM declines at the hip and knee joints which impairs the work efficiency of drawing back legs. Among the four manipulative missions, target pointing was affected less by a PPS than the other three actions.

5.2. Operational reach

ROM of the four joints was compared for the CC and PPS conditions and results are presented in Table 3.

5.2.1. ROM results

The PPS ROM results were significantly less than the CC ROM results for all test variables. Compared with the CC condition the

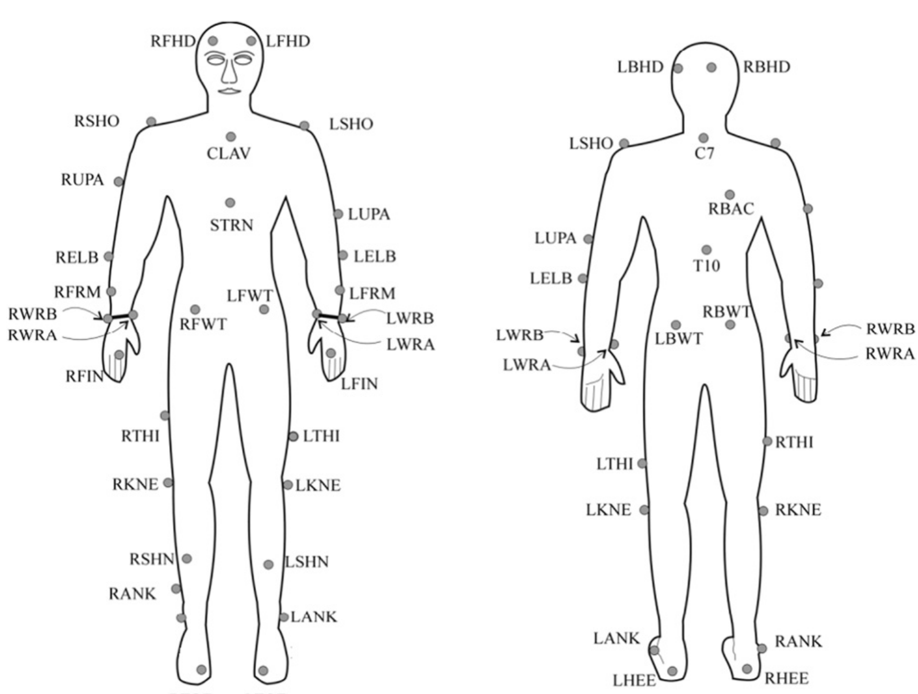

Fig. 13. Locations of the 39 reflective markers.

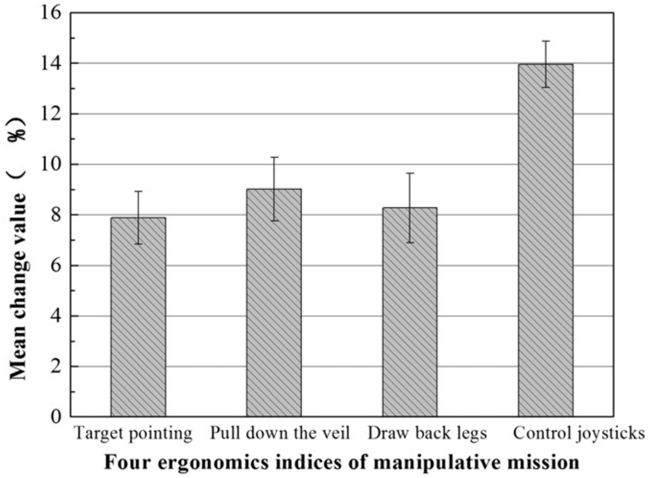

Fig. 15. Change values between CC and PPS for the four ergonomics indices of manipulative mission.

PPS significantly reduced *RS1* by 10% ($p < 0.001$), *RS2* by 8% ($p < 0.001$), *RS3* by 11% ($p < 0.01$), *RS4* by 12% ($p < 0.001$), *RS5* by 17% ($p < 0.001$), and *RS6* by 15% ($p < 0.001$). ROM of the elbow joint decreased by 8% ($p < 0.01$) in a PPS. ROM of the hip joint was also significantly decreased by 17% ($p < 0.001$) for *RH1* and 26% ($p < 0.001$) for *RH2*. The impairment in the ROM of the waist joint was also significant and *RW1* was reduced by 16% ($p < 0.001$) and *RW2* by 18% ($p < 0.001$) respectively, which indicates that the effects of a PPS on left flexion and right flexion are almost identical.

5.2.2. Discussion

This study showed that a PPS impairs the performance and greatly restricts the operational reach of a person (Fig. 16).

The changes for the six test variables of shoulder ROM are different (Fig. 16). *RS2* has the smallest impact and *RS5* the largest. It was also found that upper arm abduction required more effort than the other actions. Such findings are likely due to the differences in the difficulties of the test movements.

With the PPS the decreases in the ROM of the lower limbs was greater than that of the upper limbs (Fig. 17), while the magnitude of the changes in left and right waist flexion (*RW1*) and right flexion (*RW2*) were similar between conditions.

The experimental results show that there are some significant restrictions on the wearers' movements when wearing a PPS

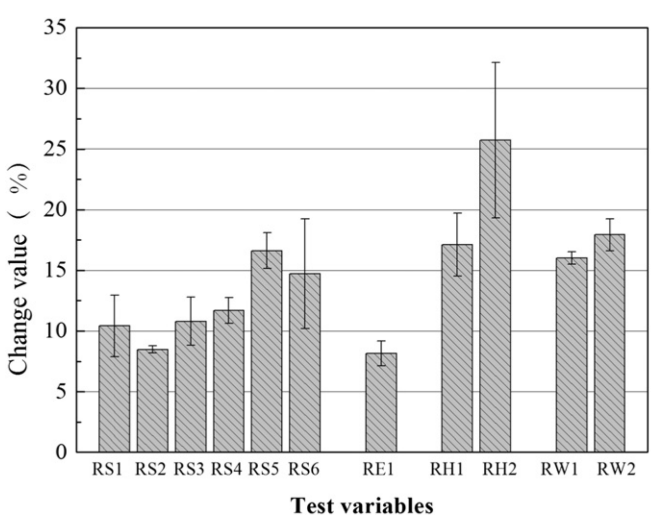

Fig. 16. Change values between CC and PPS for the test variables of operational reach.

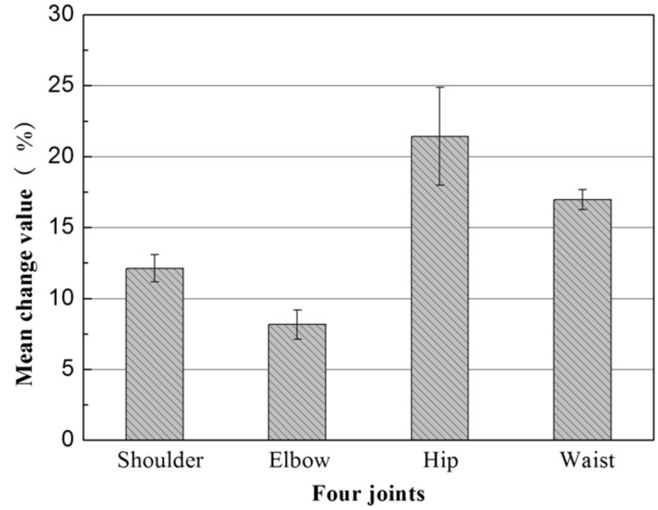

Fig. 17. Performance change values between CC and PPS of four joints.

Table 4
Systematic ergonomic appraisal indices.

Ergonomic appraisal indices of high altitude partial pressure suit		
Level 1	Level 2	Level 3
Manipulation missions	Target pointing	*TP1*
		TP2
		TP3
		TP4
	Adjusting the helmet	*PDV1*
	Drawing-back the legs	*DBL1*
		DBL2
	Control of the joystick	*CJ1*
		CJ2
		CJ3
Operational reach	ROM of shoulder joint	*RS1*
		RS2
		RS3
		RS4
		RS5
		RS6
	ROM of elbow joint	*RE1*
	ROM of hip joint	*RH1*
		RH2
	ROM of waist joint	*RW1*
		RW2
Operational strength	Grip strength	*GS1*

which needs to be considered when design the cockpit and planning a mission.

5.3. Operational strength

Table 3 indicates that *GS1* was slightly reduced by 4% with the PPS ($p < 0.01$) but *STS1* was not significantly different, showing that the PPS did not significantly adversely affect the leg exertion force. The magnitude of the grip strength change for the PPS was less than that for the manipulative mission and operational reach tasks and the PPS only had a minor adverse effect on operational strength.

6. Summary and conclusions

The aim of this study was to investigate how the wearing of a PPS affects a series of ergonomics indices mobility and performance. The ergonomics indices in this study included manipulative missions, operational reach and operational strength and each was composed of several sub-indexes. Measurements from the wearers under two experimental conditions were carried out and an effective ergonomic index system was established. Nearly all of the ergonomics indices reported in this paper showed significant and substantial detrimental effects of wearing a PPS, except for step-tread strength (*STS1*) which was unaffected. According to these results of this paper, an ergonomic evaluation index system for PPS design can be established with the three levels, as shown in Table 4.

These objective experimental data will be useful in several areas of PPS-related work. For example, designers of new suits will gain a better understanding of the ergonomics of a PPS and, therefore, maximize the wearer's work ability. In addition, our results found that the shoulder ROM for the wearers in the PPS condition was severely reduced compared with that of wearers in the CC condition. The mobility of the shoulder under suited conditions could be improved if suit designers consider this factor when they design new protective clothing in the future. This finding also provides some guidance for human factors engineers and mission planners when planning some tasks involving shoulder motions and when designing the reach envelopes to controls in a cockpit.

Numerous large and statistically significant differences associated with manipulative missions, operational reach and upper limb operational strength between the CC condition and the PPS condition have been demonstrated. These findings show that task planners and cockpit layout specialists should pay close attention to the limitations that personal protective equipment, such as a PPS, has on pilots. Moreover, these differences should also be considered in the placement of control devices and the planning of tasks. This research advances knowledge concerning the effects a PPS has on pilots. However, there are some limitations to this work. It is likely that there are other tasks that the pilot performs that were not included in this work. The test subjects were not themselves pilots and all were young and fit males. All testing was done at sea level and while seated in a stationary environment and this may be different in a pressurized and moving plane. Future studies should investigate the effects of these and other possible factors to ensure that comprehensive data are collected to improve the ergonomic design of PPS.

Acknowledgements

We are very grateful for the help in designing experiments and suggestions from Prof. Siguang Jia and Xinmin Zhang and other participants in this study.

Appendix A. Definitions of the 39 markers

Markers	Definition	Position
LFHD	Left front head	Left temple
RFHD	Right front head	Right temple
LBHD	Left back head	Left back of head
RBHD	Right back head	Right back head
C7	Seventh cervical vertebrae	Base of the neck
T10	Tenth thoracic vertebrae	Centre mid-back
CLAV	Clavicle	Top of the breast bone
STRN	Sternum	Base of the breast bone
RBAC	Right back	Centre of the right shoulder blade
LSHO	Left shoulder	Placed on the bony prominence on top of the left shoulder
LUPA	Left upper arm	Placed on the outside of the upper arm
LELB	Left elbow	Placed on the bony prominence on the outside of the elbow joint
LFRM	Left forearm	Placed on the outside of the lower arm
LWRA	Left wrist	Extended from the thumb side using a wrist bar
LWRB	Left wrist	Extended from the little finger side using a wrist bar

(*continued*)

Markers	Definition	Position
LFIN	Left finger	Placed just below the middle knuckle on the left hand
RSHO	Right shoulder	Placed on the bony prominence on top of the right shoulder
RUPA	Right upper arm	Placed on the outside of the upper arm
RELB	Right elbow	Placed on the bony prominence on the outside of the elbow joint
RFRM	Right forearm	Placed on the outside of the lower arm
RWRA	Right wrist bar thumb side	Extended from the thumb side using a wrist bar
RWRB	Right wrist bar pinkie side	Extended from the little finger side using a wrist bar
RFIN	Right finger	Placed just below the middle knuckle on the right hand
LFWT	Left Front Waist	Left Front Waist
RFWT	Right Front Waist	Right Front Waist
LBWT	Left back Waist	Left back Waist
RBWT	Right back Waist	Right back Waist
LTHI	Left thigh	Placed on the outside of the thigh below hand swing
LKNE	Left knee	Placed on the outside of the knee joint
LSHN	Left shin	Placed on the outside of the lower leg
LANK	Left ankle	Placed on the bony prominence on the outside of the ankle
LHEE	Left heel	Placed on the back of the foot
LTOE	Left toe	Placed on the tip of the big toe
RTHI	Right thigh	Placed on the outside of the thigh below hand swing
RKNE	Right knee	Placed on the outside of the knee joint
RSHN	Right shin	Placed on the outside of the lower leg
RANK	Right ankle	Placed on the bony prominence on the outside of the ankle
RHEE	Right heel	Placed on the back of the foot
RTOE	Right toe	Placed on the tip of the big toe

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Study on functional relationships between ergonomics indexes of manual performance

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Abstract

This paper investigates functional relationships between some of the key ergonomics indexes in manual performance, and attempts to condense the ergonomics appraisal indexes system and thus evaluate hand performance wearing EVA (extravehicular activity) glove, design and improve EVA glove's performance. Four types of ergonomics indexes were studied, i.e., dexterity, tactile sensibility (TS), strength and fatigue. Two test items of insert sticks into a holes-board (ISIHB) and nuts–bolts assembly task (NBAT) were used to measure dexterity, while shape discrimination (SD) was employed for TS, and grip force (GF) for strength and fatigue. The variables measured in this investigation included accomplishing time (AT) of ISIHB and NBAT, correct rate (CR) of SD, maximal grip force (MGF), instant grip force (IGF) and endurance time of grip force (ET_{GF}). Experiments were conducted on 31 undergraduates (eight female and 23 male) with two experiment conditions of bare-hand group and gloved hand group. Results demonstrated that dexterity and TS performance of gloved hand group declined significantly compared with those of bare-hand group ($p < 0.001$). There were not significant differences in strength and fatigue between two conditions ($p > 0.05$). Four effective functional relationships were developed between four pairs of ergonomics indexes in bare-hand group. In gloved hand group, in addition to above-mentioned four pairs of relationships, another formula was found, which was $\hat{y} = 0.02061 + 0.01233x$ ($p < 0.01$, dexterity and TS).

Keywords: Functional relationship; Ergonomics indexes; Manual performance; Dexterity; Tactile sensibility; Strength; Fatigue

1. Introduction

Manned space flight represents the highest level of spaceflight technology. And extravehicular activity (EVA) is one of the two primary tasks (i.e., intravehicular activity, IVA and EVA) in exploring space and developing space resource. During the EVA, astronauts are entrusted to perform tasks such as satellite deployment and retrieval, space shuttle maintenance, International Space Station (ISS) assembly as well as handle other massive objects in and around the payload. During such demanding tasks, the mission specialist must perform these tasks manually. So concerns were raised on manual performance in space EVA. Research results have been shown that hand work capabilities will decline under harsh working environments due to some special factors such as temperature, glove, pressure, and hypoxia and so on [1–4]. In order to improve hand performance or to prevent negative influence from those factors, systemic ergonomics evaluation on

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Nomenclature

TS	tactile sensibility
$ISIHB$	insert sticks into a holes-board
$NBAT$	nuts–bolts assembly task
SD	shape discrimination
GF	grip force
AT	accomplish time
CR	correct rate
MGF	maximal grip force
IGF	instant grip force
ET	endurance time
L_S	large size
M_S	middle size
S_S	small size
ET_{GF}	endurance time of grip force
$I_{ET\text{–}GF}$	the internal value of I_{GF} fitted curve and ET_{GF}
AOV	analysis of variance
AT_{ISIHB}	accomplish time of insert sticks into holes-board
AT_{NBAT}	accomplish time of nut–bolt assemble task
CR_{SD}	correct rate of shape discrimination
M_{GF}	maximal grip force
P_{AT}	performance of accomplish time
AT_T	tested accomplish time
AT_C	controlled accomplished time
P_{CR}	performance of correct rate
CR_T	tested correct rate
CR_C	control correct rate
P_S	performance of strength
MGF_T	tested maximal grip force
MGF_C	control maximal grip force
P_F	performance of fatigue
F_T	tested fatigue
F_C	control fatigue

manual performance becomes more and more necessary. But conducting such work is more difficult under space environment for the reason of badly high/low temperature or hypoxia and so forth. From former low temperature experiment of manual work efficiency we found that makes badly low temperature takes quite a long time (about 2 h–3 h) [5]. The more indexes, the longer test. At the end of experiment some physiological side-effects came to the subjects, such as hunger, fatigue, and frostbite of hands. These symptoms will impair the objectivity of experimental results. In addition, under the hypoxia condition, test items must be finished within regulated safe time in order to protect the subjects. Hence, only several ergonomics indexes can be used, which induces lack of integrality of the assessment of hand performance capability [6].

Many researchers have studied indexes functional relationships with the purpose of providing conveniences for appraising hand performance. Early in 1953, Fox et al. [9] studied the work efficiency variable responses of typists when the temperature gradually declined. As a result, they found some functional relationships between dexterity of fingers, coordination of both hands and the time exposed to low temperature. Since then, Rohmert [10] developed force exertion and endurance time functional relationships to predict muscle fatigue, while Monod et al. [11] found exponential relationship between the two indexes. O'Hara [3] was also interested in the force-endurance time relation (namely the issue of fatigue evaluation) during the course of appraising manual work efficiency. He tried to measure fatigue with transition of EMG energy spectrum, but failed to get specific relation formulas and compellent results. Bishu et al. [12] also had been engaged in this issue for many years, and till 1995 they made great improvements. In their studies systemic ergonomics measurements were conducted with the independent variables gender, glove type, pressure differential, and exertion level. Results indicated that performance of gloved hand group declined with increasing pressure differentials. The endurance time depended only on the exertion level and they were exponential relative. These conclusions were similar to those of Rohmert, Monod and Scherrer. Such findings provided support for appraising static muscle fatigue. Bishu et al. [7] hypothesized the reduction in hand performance with glove was caused by the decline of tactile sensitivity. They measured tactile sensitivity with glove using a two-point discrimination test. However, results revealed while the tactile sensibility (TS) decreased with added layers of the glove known as the thermal macrometerorite garment (TMG), on the contrary, the dexterity improved. TS and dexterity relationship was not accordant with the expected. Generally we think reduced tactile sensitivity is associated with reduced dexterity. As a follow-up of this study, they hypothesized that grasp strength could represent tactile sensitivity, but failed to find definite functional relationships. Buhman [13], Shih et al. [14] also did similar studies and draw the conclusion that for certain kinds of tactile feedback, grasp force can indeed be seen as an alternative measurement of tactile sensitivity Bensel [1] found a linear increase in times to test completion as a function of increases in thickness of the handcovering when he studied effects of various thicknesses of chemical protective gloves on manual dexterity.

From the view of physiology, hands are the actuators of brain. Manual performance is in nature the collaborative work capability of brain–hand system. Different ergonomics indexes should be correlative through the integration of brain [7]. But by now the comprehensive investigations on functional relationships between appraisal indexes of manual work efficiency at the height of indexes system have not been conducted. Only a few ergonomics indexes relations were studied in the above-mentioned work. These research conclusions were also more simple and were not sufficient to conduct comprehensive appraisal of manual work efficiency in special conditions. On the other hand, physiologically, there should be correlations between dexterity, tactile sensitivity, strength, and fatigue. However, there is little evidence of the work concerned with that aspect.

In this paper, we investigate the basic functional relationships between different appraisal indexes to condense the ergonomics indexes system of hand performance. The investigation is based on researches on appraisal indexes system of manual work efficiency of Man–Machine–Environment Engineering Institute of BUAA [4,8]. Firstly we discussed the manual performance differences caused by glove. Then the functional relationships between ergonomics indexes of two test groups were also stress researched. The ergonomics appraisal indexes investigated in this study were the optimization indexes system of EVA glove [8]. Such work is expected to provide experimental data and practice basis for condensing ergonomics appraisal indexes to shorten the evaluation time of special conditions. This study simultaneously contributes to ergonomics design of EVA glove and mission plan of astronauts who wear EVA glove.

2. Experiment design

2.1. Choice of indexes

According to previous investigation results [8,15–17], we select four types of ergonomics indexes which have the priority of performance. The research indexes and testing variables are shown in Table 1.

2.2. Experiment groups

Two groups of subjects were tested, which were bare-hand group (control group) and gloved hand group (experiment group). This investigation, different from the study on the EVA glove simulators established by Man–Machine–Environment Engineering Institute of BUAA [8], examine the effects of comfortable gloves on manual performance. Both functional relationships between ergonomics indexes of control group and experiment group have been studied.

Table 1
Research indexes and corresponding testing variables

Research indexes	Testing variables
Dexterity	AT_{ISIHB}
	AT_{NBAT}
Tactile sensitivity	CR_{SD}
Strength	M_{GF}
Fatigue	ET_{GF}
	$I_{ET\text{–}GF}$

2.3. Subjects

Thirty-one healthy undergraduates (eight female and 23 male) from BUAA participated in this investigation, their average age was 21.32 ± 0.65. All subjects were voluntary and their hand functions were normal. They all attended experiment training to understand experimental methods and manipulation regulations. Before tests, the participants must practice many times until they were able to expertly fulfill each test item and keep work ability stable.

3. Apparatus and methods

The gloves used in this research are common protective gloves for industry. They are comfortable, cottoned, and good at absorbing sweat (Fig. 1). Three sizes of gloves could be chosen according to the hand sizes of subjects and gloves' sizes were enough to fit all the 31 selected subjects.

The testing indexes and items, variables and experiment regulations of the bare-hand group and gloved hand group were identical.

3.1. Dexterity

3.1.1. Insert sticks into a holes-board

Apparatus: Insert sticks into a holes-board (ISIHB) was used to measure dexterity. The apparatus was a rectangle board with 20 uniform iron sticks and stick-holes (Fig. 2). The stick is 1.7 mm in diameter and 25 mm in length, while the stick-hole was about 2 mm in diameter. The stick-holes ranked two parallel rows.

Fig. 1. Experiment gloves (cottoned).

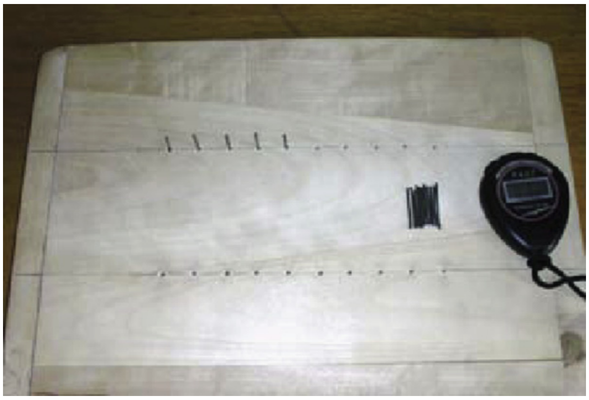

Fig. 2. ISIHB apparatus.

Methods: Firstly, the subject put 20 sticks into his left hand. Then, he was asked to insert 20 sticks into 20 stick-holes according to the regulations (Left and right hands harmonize. Lack or inclined inserting is forbidden.) as soon as possible after receiving message from experimenter. They were required to accomplish the first row from left to right firstly and then fulfill the second row. The whole process was repeated five times and each AT_{ISIHB} was recorded respectively.

3.1.2. Nuts–bolts assembly task

Apparatus: Nuts–bolts assembly task (NBAT) was also used to measure dexterity. An iron rectangular board was included, with three different bolts fixed on it (Fig. 3) lying in one line. The three kinds of size nuts suited for the bolts were also prepared. The diameters of three bolts were 16 mm (L_S), 12 mm (M_S), and 8 mm (S_S), respectively. In advance the nuts were screwed onto the bolts and their tops were level.

Fig. 3. NBAT apparatus.

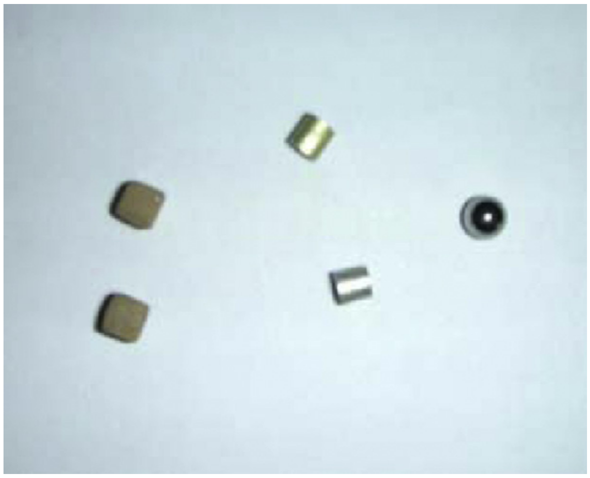

Fig. 4. TS objects.

Methods: Firstly, the subject was asked to screw the three nuts off the bolts with the sequence from L_S to S_S (from right to left seen from Fig. 3) and place them on the iron board. Then, he took up the nuts and screwed them onto the bolts with the same situation as the beginning. The whole assembly process was repeated three times and AT_{NBAT} of each process was recorded, respectively.

3.2. Tactile sensibility

Apparatus: SD was used to measure TS. Three shapes' objects were introduced in this experiment, including cubes, spheres and cylinders and their characteristic sizes were all 3 mm (Fig. 4).

Fig. 5. Hand dynamometer.

Methods: The subject closed his eyes with his right hand stretch out while the experimenter chose one object from three shapes and put it in subjects' inter-two fingers. After his feeling the subject told the object's shape as soon as possible while the apperceiving results were taken down. Each shape was repeated 10 times.

3.3. Strength and fatigue

Apparatus: GF was used to measure strength and fatigue. The apparatus was a hand dynamometer composed of a sensor and a digital display which can display the instant strength (Fig. 5). The minimum graduation is 0.1 kg and ranges from 0 to 100 kg.

Methods: Before experiment the subject grasped hand dynamometer with comfortable posture. Then he was asked to grasp the hand dynamometer to the best of his ability until IGF declined to less than 50% of MGF for consecutive three times. IGF was recorded once every two seconds. M_{GF} of all the recorded IGF was defined as strength (kg). Both ET_{GF} and I_{ET-GF} area which is the integral of I_{GF} fitted curve and ET_{GF} (I_{ET-GF}, kg s) represented fatigue.

3.4. Measurement of performance

In this study, in order to unify the comparing criterion for effects of gloves on each ergonomics index, no-dimension "performance" indexes are introduced. The more decline of index performance indicates the more serious effects of the gloves on the index, and the more sensitivity of the index. The calculations of the performance indexes are as follows:

$$P_{AT}(\%) = \left(1 - \frac{AT_{\mathrm{T}} - AT_{\mathrm{C}}}{AT_{\mathrm{C}}}\right) \times 100\% \tag{1}$$

$$P_{CR}(\%) = \left(1 + \frac{CR_{\mathrm{T}} - CR_{\mathrm{C}}}{CR_{\mathrm{C}}}\right) \times 100\% \tag{2}$$

$$P_{\mathrm{S}}(\%) = \left(1 + \frac{MGF_{\mathrm{T}} - MGF_{\mathrm{C}}}{MGF_{\mathrm{C}}}\right) \times 100\% \tag{3}$$

$$P_{\mathrm{F}}(\%) = \left(1 + \frac{F_{\mathrm{T}} - F_{\mathrm{C}}}{F_{\mathrm{C}}}\right) \times 100\% \tag{4}$$

3.5. Statistical analysis

Regression analysis and paired-sample T test (analysis of variance, AOV) were conducted on the data by the form of average and STDEV ($\overline{x} \pm s$) by SPSS 12.0 for Windows and OriginPro7.5. The limit of significant variance was $p < 0.05$.

4. Results

4.1. Dexterity

4.1.1. Insert sticks into a holes-board

There were 29 subjects who attended ISIHB test. From Table 2 it can be found that AT_{ISIHB} of gloved hand group significantly prolongs ($p < 0.001$) compared with that of bare-hand group. Performance of gloved hand group decreases 11.7%, which shows that gloves significantly impair the dexterity.

4.1.2. Nuts–bolts assembly task

The same 29 subjects participated in NBAT test. Table 2 shows us that the AT of assembling each size of nuts is significantly affected by gloves. The performance of each size nut declines with different degree. Performance of S_{S} nut is impaired most seriously and loss of performance is 32.2%. L_{S} takes the second (26.8%) and M_{s} is affected least (21.9%). The total AT of completing three nuts assembly task also significantly prolongs ($p < 0.001$) after wearing glove. The loss of P_{AT} (24.9%) remarkably exceeds that of ISIHB (11.7%), which demonstrates that NBAT is much more sensitive to glove than ISIHB. So when we appraise dexterity of glove, NBAT has the priority.

4.2. Shape discrimination

Twenty eight subjects took part in SD test. Table 2 indicates CR_{SD} significantly declines after donning glove ($p < 0.001$) and P_{CR} reduces 12.5% which shows glove impairs TS considerably.

Table 2
AOV summary of five indexes

Test indexes	Samples (n)	Test variables	Bare-handed group[a]	Gloved group	Loss of performance (%)
ISIHB	29	AT_{ISIHB} (s)	29.1 ± 3.1	$32.3 \pm 3.7^{***}$	11.7
L_{S}			5.5 ± 1.0	$6.8 \pm 1.4^{***}$	26.8
M_{S}	29	AT_{NBAT} (s)	7.0 ± 1.3	$8.4 \pm 1.4^{***}$	21.9
NBAT					
S_{S}			6.1 ± 1.6	$7.7 \pm 2.2^{**}$	32.2
Total			18.5 ± 3.2	$22.9 \pm 4.3^{***}$	24.9
SD	28	CR_{SD} (%)	93.1 ± 7.1	$82.0 \pm 12.0^{***}$	12.1
Strength	28	M_{GF} (kg)	32.6 ± 9.4	33.4 ± 9.7	−4.2
Fatigue	28	ET_{GF} (s)	50.1 ± 22.5	52.7 ± 17.3	−12.8

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.
[a]Compared with control group.

4.3. Strength and fatigue

Twenty eight subjects participated in strength and fatigue test. There are no significant differences in the M_{GF}, ET_{GF} and I_{ET-GF} ($p > 0.05$, Table 2) after wearing glove. Experiment results show that glove does not affect strength and fatigue, which is consistent with other investigations [7].

5. Functional relationships between indexes of bare-hand group

5.1. ISIHB–NBAT relationship

The experiment data from 26 subjects who participated in all tests were investigated in order to explore ISIHB–NBAT functional relationship. Here M_{S} assembly task denotes NBAT. In order to unify magnitude with AT_{ISIHB}, according to the characteristics of data, the AT_{NBAT} of M_{S} (i.e., $AT_{\mathrm{NBAT}\text{-}M_{\mathrm{s}}}$) was magnified four times. By AOV we found that there was no significant variance between AT_{ISIHB} and AT_{NBAT} ($p > 0.05$). This finding indicates that two dexterity indexes can substitute each other.

Supposing $x = AT_{\mathrm{NBAT}} = 4 \times AT_{\mathrm{NBAT}-M_{\mathrm{S}}}$, $y = AT_{\mathrm{ISIHB}}$, by regression analysis of 26 paired data, the unitary linear regression equation was obtained by

$$\hat{y} = 16.108 + 0.467x, \quad 21.07 \leqslant x \leqslant 38.25 \tag{5}$$

$$R = 0.647 > R_{0.001}(n-2) = 0.496$$

$$P = 0.000353 < 0.001$$

Fig. 6 shows this regression equation was very effective and the linearity between variables x and y was significant. Thus, any one of ISIHB and NBAT can be chosen to investigate dexterity of hands in the further study.

5.2. Dexterity–strength relationship

Strength (x)–dexterity (y) functional relationship can be obtained by regression analysis as follows:

$$\hat{y} = 0.02546 + 2.3686 \times 10^{-4}x \tag{6}$$

where the coefficient of relativity

$$|R| = 0.48542 > R_{0.05}(n-2)$$

Such result shows the regression equation is effective ($p < 0.05$) and the linear relativity of dexterity and strength is significant. Dexterity is directly proportional to strength.

5.3. Dexterity–fatigue relationship

It has been found from regression analysis of dexterity and ET_{GF} that the linear relativity is not significant ($p > 0.05$). Reason for this result might be the test time of dexterity being too short, and generally the subject is far from fatigue in such short time. Moreover, the test items of dexterity used in this experiment need less strength, so it is almost independent of fatigue.

5.4. Dexterity–TS relationship

AT_{ISIHB} represents dexterity. As we all know that dexterity is inversely proportional to AT, so we define

$$x = CR_{SD}$$

$$y = 1/AT_{ISIHB}$$

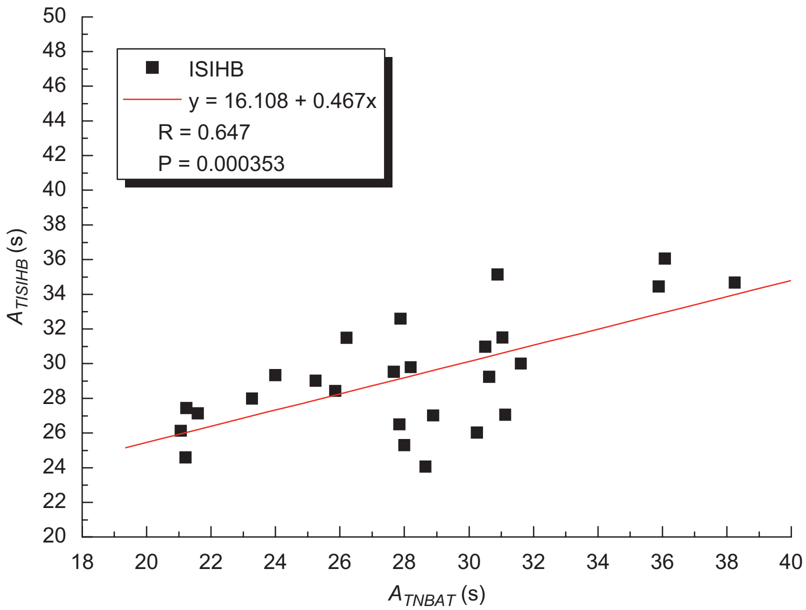

Fig. 6. Regression analyses of ISIHB and NBAT.

It can be obtained from the regression analysis and test of coefficient of relativity that

$$R = 0.1258$$

$$|R| = 0.1258 < R_{0.05}(n-2) = R_{0.05}(24) = 0.388$$

This result indicates the linear relation between dexterity and TS is not significant, which means the dexterity is independent of TS.

5.5. Dexterity, TS, and strength relationship

Suppose $x_1 = CR_{\mathrm{SD}}$, $x_2 = M_{GF}$, $y = 1/AT_{\mathrm{ISIHB}}$. For sample number $n = 26$, factor number $m = 2$, then it is assumed that the functional relationship of three indexes was

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 \tag{7}$$

With least squares we know that b_0, b_1, and b_2 should make summation of square deviation (Q) of total experiment value (y_i, $i = 1, 2, \ldots, 26$) and regression value ($\hat{y}_i$) least, i.e.,

$$Q = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 = \sum_{i=1}^{n}(y_i - b_0 - b_1 x_{i1} - b_2 x_{i2})^2 = Q_{\min} \tag{8}$$

By limit theorem of calculus, b_0, b_1, and b_2 should be the solutions of the regular equations group:

$$\begin{cases} \dfrac{\partial Q}{\partial b_0} = -2\sum_{i=1}^{n}(y_i - b_0 - b_1 x_{i1} - b_2 x_{i2}) = 0 \\ \dfrac{\partial Q}{\partial b_1} = -2\sum_{i=1}^{n}(y_i - b_0 - b_1 x_{i1} - b_2 x_{i2})x_{i1} = 0 \\ \dfrac{\partial Q}{\partial b_2} = -2\sum_{i=1}^{n}(y_i - b_0 - b_1 x_{i1} - b_2 x_{i2})x_{i2} = 0 \end{cases} \tag{9}$$

Substituting the experiment data into the function and calculated by Matlab we have

$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 0.012013 \\ 0.015648 \\ 0.000213 \end{bmatrix} \tag{10}$$

So the regression equation of dexterity, SD, and strength was got as follows:

$$\hat{y} = 0.012013 + 0.015648 x_1 + 0.000213 x_2 \tag{11}$$

where

$$0.7667 \leqslant x_1 \leqslant 1, \quad 18 \leqslant x_2 \leqslant 50.2 \tag{12}$$

The analysis result of SPSS shows

$$F = 4.243 > F_{0.05}(2, 23) = 3.42 \tag{13}$$

Such result indicates that the regression equation is effective and the linear relationship of y, x_1, and x_2 is significant. If experiment conditions are limited, based

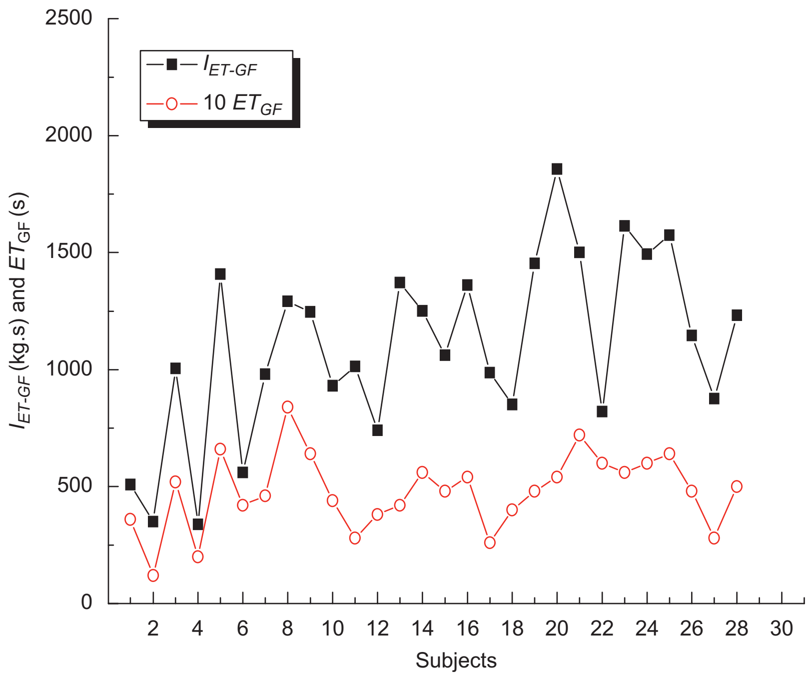

Fig. 7. Comparison of I_{ET-GF} and ET_{GF}.

on this equation, two of the three indexes could be tested to predict the value of the third index.

However, because the unit of each coefficient is not uniform, it is difficult to tell which one of x_1 and x_2 contributes more to y only from the magnitude of b_1 and b_2. Hence the regression coefficient should be unified. Supposing the standardization regression coefficient of b_j is B_j, and

$$B_j = |b_j|\sqrt{\frac{L_{jj}}{L_{yy}}} \quad \text{there } L_{jj} = \sum_{i=1}^{n}(x_{ij} - \overline{x}_j)^2,$$

$$L_{yy} = \sum_{i=1}^{n}(y_i - \overline{y})^2, \quad j = 1, 2, \ldots, m \tag{14}$$

The larger B_j is, the more important the factor is. For the above-mentioned regression equation, it becomes

$$B_1 = |b_1|\sqrt{\frac{L_{11}}{L_{yy}}} = 0.01564775\sqrt{\frac{0.132191043}{0.033261206}} = 0.031195$$

$$B_2 = |b_2|\sqrt{\frac{L_{22}}{L_{yy}}} = 0.0002129\sqrt{\frac{1847.946154}{0.033261206}} = 0.050182$$

Thus

$$B_2 > B_1 \tag{15}$$

So it can be thought that x_2 is more important than x_1, namely strength contributes more greatly to dexterity than SD.

5.6. TS–strength relationship

Relation of CR_{SD} and M_{GF} was analyzed and the result showed $p > 0.05$ which means strength and TS is irrelevant. This work [7] indicated human is born with the ability of optimizing. When a person takes up one object, his TS will automatically adjust him to use the smallest strength. Physiologically, there must be some relationships between TS and strength. But this strength is the least for taking up objects, not the MGF of this experiment. The MGF and the least strength are not correlated from the view of physiology.

5.7. TS–fatigue relationship

The relation of CR_{SD} and ET_{GF} were also analyzed. Results show $p = 0.635 > 0.05$ which means TS and fatigue are irrelevant. That is to say that the CR_{SD} is independent of ET_{GF}.

5.8. I_{ET-GF}–ET_{GF} relationship

It can be seen from the tendency figure of I_{ET-GF} and 10 times ET_{GF} that their change laws are consistent.

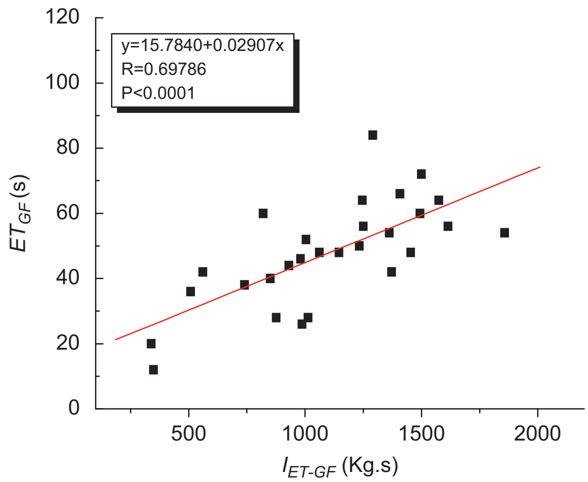

Fig. 8. Fitted line of I_{ET-GF} and ET_{GF}.

That is especially true for the female (the initial eight subjects in Fig. 7), the change in tendency is almost the same.

Supposing $x = I_{ET-GF}$, $y = ET_{GF}$, regression equation can be got as follows:

$$\hat{y} = 15.784 + 0.02907x \tag{16}$$

where

$$338.619 \leqslant x \leqslant 1857.26$$

By variance analysis:

$$R = 0.69786$$

$$|R| = 0.69786 > R_{0.0001}(n-2), \quad n = 28$$

It shows that ET_{GF} and I_{ET-GF} is linear relative ($p < 0.0001$, Fig. 8). So we can conclude that, two representation forms (ET_{GF} and I_{ET-GF}) of fatigue are generally exchangeable.

5.9. Strength–fatigue relationship

According to Section 5.8, ET_{GF} is chosen to represent fatigue for it being simpler to get than I_{ET-GF}. If $y = ET_{GF}$, $x = M_{GF}$, by regression analysis and variance test it can be found that these two indexes have no linear relativity ($p > 0.05$).

6. Functional relationships between indexes of gloved hand group

From Table 2 we can see that glove significantly impairs dexterity and TS. Thus, besides above-mentioned effective linear relativity, the dexterity–TS relationship was also studied in gloved hand group which was not significant in bare-hand group. Here strength and fatigue indexes were not investigated again because they are not sensitive to glove.

6.1. ISIHB–NBAT relationship

The way of analyzing these two indexes is same to the bare-hand group. By regression analysis *ISIHB–NBAT* relationship is

$$\hat{y} = 22.80224 + 0.29593x \quad (27.373 \leqslant x \leqslant 47.067) \tag{17}$$

where

$$|R| = 0.466 > R_{0.05}(26) = 0.374$$

Such results show the linear regression equation of two indexes is effective and the linear relativity of ISIHB and NBAT is also significant ($p < 0.05$). Such conclusion is consistent with that of bare-hand group.

6.2. Dexterity–strength relationship

If $y = 1/AT_{\mathrm{ISIHB}}$, $x = M_{GF}$, by regression analysis the following equation is obtained:

$$\hat{y} = 0.0272 + 0.00012x \quad (11 \leqslant x \leqslant 52) \tag{18}$$

There the relativity was tested by *R-Test*. Test result reveals $p < 0.05$ which means that regression equation is effective and the linear relativity of dexterity and strength is significant. Such conclusion is accordant to that of bare-hand group.

6.3. Dexterity–TS relationship

Supposing $y = 1/AT_{\mathrm{ISIHB}}$, $x = M_{GF}$, by regression it can be got:

$$\hat{y} = 0.02061 + 0.01233x \quad (0.5667 \leqslant x \leqslant 1) \tag{19}$$

There the regression coefficient is

$$R = 0.519 > R_{0.01}(n-2) = 0.505$$

This result indicates equation is effective and the linear relativity of dexterity and TS is very significant. Formula (19) indicates dexterity is direct proportional to TS.

This finding is different from bare-hand group, which shows glove not only affects TS but also impairs careful dexterity task, so that changes the relation of two indexes. Performance difference from glove makes dexterity and TS correlative each other.

6.4. Dexterity, TS, and strength relationship

Known from Section 5.5, dexterity, TS, and strength are linear relative. There further investigations are conducted on whether the relativity of three indexes exists or not.

Suppose

$$y = 1/AT_{ISIHB}, \quad x_1 = CR_{SD}, \quad x_2 = M_{GF}$$

By regression analysis the following equation is obtained:

$$\hat{y} = 0.0122296 + 0.0169424x_1 + 0.0001385x_2, \quad 0.6333 \leqslant x_1 \leqslant 1,\ 11.2 \leqslant x_2 \leqslant 43.2 \tag{20}$$

The results of variance analysis by SPSS and *F-Test* show:

$$F = 6.572 > F0.01(2, 20) = 5.85$$

This indicates equation is effective and the linear relativity of dexterity and strength still exists in gloved hand group.

In this formula $p_1 < 0.01$, $p_2 < 0.05$, $B_1 = 0.042515$, and $B_2 = 0.034454$. These results show b_1 and b_2 have significant meaning, namely the impacts on dexterity caused by TS and strength is very significant. At the same time $B_1 > B_2$ indicates x_1 contributes more to dexterity than x_2, that is to say the influencing extent of TS on dexterity is greater than that of strength. Such conclusions illustrate the performance of conducting careful task of dexterity mainly depends on TS (in ISIHB task the diameter of holes and sticks are all very small, so it belongs to careful task).

7. Discussion

Performances of bare-hand group and gloved hand group were compared. From the results (Table 2) we can see glove significantly affected manual performance. But performance degradation of different indexes is different. Among the four ergonomics indexes, dexterity is the most sensitive to gloves, and SD takes the second place. Strength and fatigue were not significantly affected by the glove used in this research. So while evaluating the glove ergonomics (such kind glove as tested in this study) only the indexes of dexterity and SD were necessary.

The performance changes extent of two dexterity test items (i.e., ISIHB and NBAT) is not also different. Loss of performance of ISIHB was 11.7%, and which of NBAT of L_s, M_s, S_s, and total sizes was, respectively, 26.8%, 21.9%, 32.2%, and 24.9 (Table 2). Such findings indicate NBAT was more sensitive to glove than ISIHB. NBAT should be the optimal test item to analyze dexterity. And the three sizes of NBAT were affected by glove with different extent. For synthetically examining manual performance the NBAT test should include three kinds of sizes nuts and bolts assembly task. Namely the total AT_{NBAT} should be the best examination on dexterity.

The most important findings of this research are functional relationships between ergonomics indexes of bare-hand group and gloved hand group. The findings indicated ISIHB and NBAT were linear relative whether the bare-hand group or the gloved hand group. This kind of proportional relation suggests when we examine dexterity of manual work only choosing one of the two indexes is enough. Moreover under some harsh conditions, when one of them is difficult to be used to test dexterity, the other one can substitute it. But the proportional coefficients of two groups namely test conditions are different. Applying this relation the coefficient should be decided by the type of glove. So such investigations on EVA glove should be conducted for the research practice of EVA.

In bare-hand group dexterity and TS was not relative. However, in gloved hand group dexterity was direct proportional to TS. This finding indicates relations between indexes will change with hand wearing conditions. Of course further research should be done on this issue.

Dexterity was also synchronously linear relative to strength and TS under two test conditions. This relation showed that dexterity can synchronously reflect the characteristics of strength and TS. Dexterity can act as a synthetical ergonomics index for investigation on manual performance. But the contribute levels to dexterity change after wearing glove. Glove not only affects indexes performance but also proportional relation between indexes.

ET_{GF} and I_{GF-ET} area was also linear, so the simple variable, i.e., ET_{GF}, should be the optimal index to test fatigue.

8. Conclusions and future works

Investigations demonstrate that glove significantly impairs dexterity and TS of hands. Functional relationships between ergonomics indexes of manual performance are found, which also exist in gloved hand group.

Four pairs of functional relationships (i.e., ISIHB–NBAT, Dexterity–strength, I_{ET-GF}–ET_{GF} and Dexterity–TS–strength) exist in bare-hand group.

Besides the above linear relations, another linear relativity is found between dexterity and TS in gloved hand group. These findings suggest that the ergonomics appraisal indexes system of manual performance can be condensed.

In addition, glove not only impairs manual performance but also influences functional relationships between indexes and interrelated coefficients. In future investigations, more work need to be done in order to apply these conclusions into practical appraisal of manual performance in the harsh environment of space.

These research findings provide basal data for evaluation of manual performance, training and instruction of cosmonauts, ergonomics design, characteristic analysis and improvement of EVA glove, and EVA mission plan.

Further researches should be conducted on real EVA glove so that investigation results can be directly applied to astronautics ergonomics.

Acknowledgments

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（关于学生第一作者导师第二作者署名关系的证明）

单位：生物与医学工程学院

姓名	丁立	工作证号	07441	现任职称	副教授	任职时间	2002.9
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5	刘何庆	SY0710107	丁立				
6	李晶	SY0810111	丁立				
7	张春光	SY0810126	丁立				
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16	张静	SY1410217	丁立				

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单位审核人签字：　　　　日期：2016年5月19日

单位审核人签字（加盖公章）：　　　　日期：2016年5月19日

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文献收录检索证明

作者姓名：丁立 (Ding，Li)

经检索“网络版科学引文索引（SCI-EXPANDED）”数据库，该作者发表的论文（2004-2016 年），被收录 7 篇。

检索结果见附件，共 5 页。

检索时间为 2016 年 5 月 19 日。

特此证明！

证明人（签字）：惠瑶

证明单位（盖章）：北京航空航天大学图书馆

二〇一六年五月十九日

附件：

第 1 条，共 7 条

标题: Effects of EVA gloves on grip strength and fatigue under low temperature and low pressure

作者: Tian, YS (Tian, Yinsheng); Ding, L (Ding, Li); Liu, HQ (Liu, Heqing); Li, Y (Li, Yan); Li, DY (Li, Deyu); Wang, L (Wang, Li)

来源出版物: APPLIED ERGONOMICS 卷: 53 页: 17-24 **DOI:** 10.1016/j.apergo.2015.08.010 子辑: A 出版年: MAR 2016

Web of Science 核心合集中的 "被引频次": 0

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入藏号: WOS:000367776200003

语种: English

文献类型: Article

地址: [Tian, Yinsheng; Ding, Li; Liu, Heqing; Li, Yan; Li, Deyu] Beihang Univ, Sch Biol Sci & Med Engn, Beijing 100191, Peoples R China.

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来源出版物页码计数: 8

第 2 条，共 7 条

标题: Muscle weakness is related to slip-initiated falls among community-dwelling older adults

作者: Ding, L (Ding, Li); Yang, F (Yang, Feng)

来源出版物: JOURNAL OF
BIOMECHANICS 卷: 49 期: 2 页: 238-243 **DOI:** 10.1016/j.jbiomech.2015.12.009 出版年: JAN 25 2016

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文献类型: Article

地址: [Ding, Li] Beihang Univ, Sch Biol Sci & Med Engn, Beijing 100191, Peoples R China.

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第 3 条，共 7 条
标题: Optimizing the physical ergonomics indices for the use of partial pressure suits
作者: Ding, L (Ding, Li); Li, XX (Li, Xianxue); Hedge, A (Hedge, Alan); Hu, HM (Hu, Huimin); Feathers, D (Feathers, David); Qin, ZF (Qin, Zhifeng); Xiao, HJ (Xiao, Huajun); Xue, LH (Xue, Lihao); Zhou, QX (Zhou, Qianxiang)
来源出版物: APPLIED ERGONOMICS **卷:** 47 **页:** 72-83 **DOI:** 10.1016/j.apergo.2014.08.021 **出版年:** MAR 2015
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入藏号: WOS:000347663600009
语种: English
文献类型: Article
地址: [Ding, Li; Li, Xianxue; Zhou, Qianxiang] Beihang Univ, Sch Biol Sci & Med Engn, Minist Educ, Key Lab Biomech & Mechanobiol, Beijing 100191, Peoples R China.
[Hedge, Alan; Feathers, David] Cornell Univ, Coll Human Ecol, Dept Design & Environm Anal, Ithaca, NY 14853 USA.
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第 4 条，共 7 条
标题: The effects of pressurized partial pressure suits on operational ergonomics
作者: Hu, HM (Hu, Huimin); Ding, L (Ding, Li); Hedge, A (Hedge, Alan); Li, XX (Li, Xianxue); Zhang, CG (Zhang, Chunguang); Qin, ZF (Qin, Zhifeng); Xiao, HJ (Xiao, Huajun)
来源出版物: INTERNATIONAL JOURNAL OF INDUSTRIAL ERGONOMICS **卷:** 45 **页:** 107-115 **DOI:** 10.1016/j.ergon.2014.12.010 **出版年:** FEB 2015

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文献类型: Article
地址: [Hu, Huimin; Ding, Li; Li, Xianxue; Zhang, Chunguang] Beihang Univ, Sch Biol Sci & Med Engn, Beijing 100191, Peoples R China.
[Hu, Huimin] China Natl Inst Standardizat, Beijing 100088, Peoples R China.
[Hedge, Alan] Cornell Univ, Dept Design & Environm Anal, Coll Human Ecol, Ithaca, NY 14853 USA.
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第 5 条，共 7 条
标题: An experimental study on the ergonomics indices of partial pressure suits
作者: Li, XX (Li, Xianxue); Ding, L (Ding, Li); Hedge, A (Hedge, Alan); Hu, HM (Hu, Huimin); Qin, ZF (Qin, Zhifeng); Zhou, QX (Zhou, Qianxiang)
来源出版物: APPLIED ERGONOMICS **卷:** 44 **期:** 3 **页:** 393-403 **DOI:** 10.1016/j.apergo.2012.10.003 **出版年:** MAY 2013
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入藏号: WOS:000314447000008
语种: English
文献类型: Article
地址: [Li, Xianxue; Ding, Li; Zhou, Qianxiang] Beihang Univ, Key Lab Biomech & Mechanobiol, Minist Educ, Sch Biol Sci & Med Engn, Beijing 100191, Peoples R China.
[Hedge, Alan] Cornell Univ, Dept Design & Environm Anal, Coll Human Ecol, Ithaca, NY 14853 USA.
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第 6 条，共 7 条

标题: Study on functional relationships between ergonomics indexes of manual performance
作者: Hu, HM (Hu, Hui-Min); Ding, L (Ding, Li); Chen, SP (Chen, Shou-Ping); Yang, CX (Yang, Chun-Xin); Yuan, XG (Yuan, Xiu-Gan)
来源出版物: ACTA ASTRONAUTICA **卷:** 63 **期:** 7-10 **页:** 811-821 **DOI:** 10.1016/j.actaastro.2008.02.016 **出版年:** OCT-NOV 2008
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文献类型: Article
地址: [Hu, Hui-Min; Chen, Shou-Ping; Yang, Chun-Xin; Yuan, Xiu-Gan] Beijing Univ Aeronaut & Astronaut, Sch Aeronaut Sci & Engn, Beijing 100083, Peoples R China.
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IDS 号: 351FE
ISSN: 0094-5765
来源出版物页码计数: 11

第 7 条，共 7 条

标题: The research of EMU glove heating system
作者: Ding, L (Ding, L); Yuan, XG (Yuan, XG); Lei, Q (Lei, Q); Yu, YH (Yu, YH)
来源出版物: AEROSPACE SCIENCE AND TECHNOLOGY **卷:** 8 **期:** 2 **页:** 93-99 **DOI:** 10.1016/j.ast.2003.04.002 **出版年:** MAR 2004
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语种: English
文献类型: Article
地址: Kunming Univ Sci & Technol, Sch Transportat, Kunming 650051, Peoples R China.
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IDS 号: 803MP
ISSN: 1270-9638
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文献收录检索证明

作者姓名：丁立 (Ding，Li)

经检索“网络版社会科学引文索引（SSCI）”数据库，该作者发表的论文（2004 年-2016 年），被收录 1 篇。

检索结果见附件，共 1 页。

检索时间为 2016 年 5 月 19 日。

特此证明！

证明人（签字）：惠瑶

证明单位（盖章）：北京航空航天大学图书馆

二〇一六年五月十九日

附件：

第 1 条，共 1 条

标题: Simulating extreme environments: Ergonomic evaluation of Chinese pilot performance and heat stress tolerance

作者: Li, J (Li, Jing); Tian, YS (Tian, Yinsheng); Ding, L (Ding, Li); Zou, HJ (Zou, Huijuan); Ren, ZS (Ren, Zhaosheng); Shi, LY (Shi, Liyong); Feathers, D (Feathers, David); Wang, N (Wang, Ning)

来源出版物: WORK-A JOURNAL OF PREVENTION ASSESSMENT & REHABILITATION **卷:** 51 **期:** 2 **页:** 215-222 **DOI:** 10.3233/WOR-141842 **出版年:** 2015

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语种: English

文献类型: Article

地址: [Li, Jing; Tian, Yinsheng; Ding, Li] Beihang Univ, Sch Biol Sci & Med Engn, Beijing 100191, Peoples R China.

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文献收录检索证明

作者姓名：丁立 (Ding，Li)

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特此证明！

证明人（签字）：惠瑶

证明单位（盖章）：北京航空航天大学图书馆

二Ｏ一六年五月十九日

附件：

1. **Simulation on thermal control system of the extravehicular spacesuit**
Li, Tanqiu (School of Aeronautic Science and Engineering, Beihang University, No.37 XueYuan Road, HaiDian District, Beijing 100191, China); Zhang, Jing; Yuan, Xiugan; Ding, Li **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 8529 LNCS, p 112-123, 2014, *Digital Human Modeling: Applications in Health, Safety, Ergonomics and Risk Management - 5th International Conference, DHM 2014, Held as Part of HCI International 2014, Proceedings*
Database: Compendex
Accession number: 20142417801356

2. **Study on the evaluation of automotive seat comfort during prolonged simulated driving**
Li, Xianxue (Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, School of Biological Science and Medical Engineering, Beihang University, Beijing, China); Ding, Li; Zhou, Qianxiang; Hu, Huimin; Zhao, Chaoyi **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 8529 LNCS, p 101-111, 2014, *Digital Human Modeling: Applications in Health, Safety, Ergonomics and Risk Management - 5th International Conference, DHM 2014, Held as Part of HCI International 2014, Proceedings*
Database: Compendex
Accession number: 20142417801355

3. **Study on operating clearance measurement of some connectors by using motion capture**
Du, Hao (Biological and Medical Engineering School of Beihang University, Beijing, China); Wang, Li; Ding, Li; Xu, Yulin; Jiang, Changhua **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 9187, p 45-53, 2015, *Design, User Experience, and Usability: Users and Interactions - 4th International Conference, DUXU 2015 Held as Part of HCI International 2015, Proceedings*
Database: Compendex
Accession number: 20154701582709

4. **Comfort evaluation for aircraft seat cushion based on finite element model**
Li, Xianxue (School of Biological Science and Medical Engineering,

Beijing University of Aeronautics and Astronautics, Beijing, China); Ding, Li; Wang, Xingwei; Wei, Shihua; Zhou, Qianxiang; Hu, Huimin **Source:** *Beijing Hangkong Hangtian Daxue Xuebao/Journal of Beijing University of Aeronautics and Astronautics*, v 41, n 2, p 241-245, February 1, 2015
Language: Chinese
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Accession number: 20151900817551

5. **Biomechanical analysis of human thorax and abdomen during automotive impact**
Hu, Hui-min (China National Institute of Standardization, Beijing, China); Ding, Li; Li, Xianxue; Zhao, Chaoyi; Yin, Yan **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 9185, p 266-273, 2015, *Digital Human Modeling: Applications in Health, Safety, Ergonomicsand Risk Management: Ergonomics and Health - 6th International Conference, DHM 2015 Held as Part of HCI International 2015, Proceedings*
Database: Compendex
Accession number: 20154201396972

6. **Development of a 3D finite element model of the Chinese 50th male for the analysis of automotive impact**
Hu, Hui-Min (China National Institute of Standardization, Beijing, China); Ding, Li; Li, Xianxue; Zhao, Chaoyi; Yin, Yan **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 9185, p 258-265, 2015, *Digital Human Modeling: Applications in Health, Safety, Ergonomicsand Risk Management: Ergonomics and Health - 6th International Conference, DHM 2015 Held as Part of HCI International 2015, Proceedings*
Database: Compendex
Accession number: 20154201396971

7. **The Relationship between Active Heating Power and Temperature of the Fingers in EVA Glove**
Tian, Yinsheng (School of Biological Science and Medical Engineering, Beihang University, No.37 XueYuan Road, HaiDian District, Beijing, 100191, China); Li, Ding; Liu, Heqing **Source:** *Communications in Computer and Information Science*, v 434 PART I, p 123-128, 2014, *HCI International 2014 - Posters' Extended Abstracts - International Conference, HCI International 2014, Proceedings*
Database: Compendex
Accession number: 20142717908819

8. **Optimization for lunar mission training scheme based on AnyBody software**
Zhang, Jing (School of Biological Science and Medical Engineering, Beihang University, Beijing, China); Zhou, Rong; Li, Jingwen; Ding, Li; Wang, Li **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 8026 LNCS, n PART 2, p 169-178, 2013, *Digital Human Modeling and Applications in Health, Safety, Ergonomics, and Risk Management: Human Body Modeling and Ergonomics*
Database: Compendex
Accession number: 20132916504904

9. **Simulation and application on aviators' lung injury during rapid decompression of cabin**
Li, Jingwen (School of Biological Science and Medical Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China); Xiao, Huajun; Ding, Li; Shi, Haiwen **Source:** *Beijing Hangkong Hangtian Daxue Xuebao/Journal of Beijing University of Aeronautics and Astronautics*, v 39, n 7, p 890-896, July 2013 **Language:** Chinese
Database: Compendex
Accession number: 20134316887279

10. **Hemodynamic simulation of partial pressure suits under pressure**
Yang, Tao (School of Biological Science and Medical Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China); Ding, Li; Zhang, Chunguang; Qin, Zhifeng **Source:** *Beijing Hangkong Hangtian Daxue Xuebao/Journal of Beijing University of Aeronautics and Astronautics*, v 39, n 8, p 1122-1126, August 2013 **Language:** Chinese
Database: Compendex
Accession number: 20134316887323

11. **Research of human thermal model when dividing hand into poly-segment**
Ding, Li; Sang, Min-Jing; Yuan, Xiu-Gan **Source:** *Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics*, v 27, n 5, p 832-834, September 2006 **Language:** Chinese
Database: Compendex
Accession number: 20064410215373

12. **EVA glove strength under low temperature and pressure**
Liu, Heqing (School of Biological Science and Medical Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China); Ding, Li; Yuan, Xiugan; Li, Jing **Source:** *Beijing Hangkong Hangtian Daxue Xuebao/Journal of Beijing University of Aeronautics and Astronautics*, v 36, n 11, p 1311-1314+1342, November 2010 **Language:**

Chinese
Database: Compendex
Accession number: 20110113542670

13. **Experimental study on thermal conductivity coefficient of clothing materials in especial environment**
Ding, Li (School of Biologic Science and Medical Engineering, Beihang University, Beijing 100191, China); Lei, Yan-Peng; Wang, Chao; Yuan, Xiu-Gan **Source:** *Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics*, v 30, n 2, p 318-320, February 2009 **Language:** Chinese
Database: Compendex
Accession number: 20091011946498

14. **Mechanical ergonomics analysis of capstan partial pressure suit under pressure**
Zhang, Chunguang (School of Biological Science and Medical Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China); Ding, Li; Qin, Zhifeng; Xiao, Huajun **Source:** *Beijing Hangkong Hangtian Daxue Xuebao/Journal of Beijing University of Aeronautics and Astronautics*, v 37, n 8, p 953-957, August 2011 **Language:** Chinese
Database: Compendex
Accession number: 20114214431888

15. **Hand performance changes under acute exposure to moderate and mild hypobaric hypoxia**
Qin, Zhifeng (School of Aeronautics Science and Engineering, Beihang University, China); Hu, Huimin; Ding, Li; Xiao, Huajun; Li, Jing **Source:** *2011 International Conference on Remote Sensing, Environment and Transportation Engineering, RSETE 2011 - Proceedings*, p 7617-7622, 2011, *2011 International Conference on Remote Sensing, Environment and Transportation Engineering, RSETE 2011 - Proceedings*
Database: Compendex
Accession number: 20113614293702

16. **Biomechanical simulation and verification of astronaut extravehicular activities**
Li, Jing-Wen (School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China); Ding, Li; Yang, Ai-Ping **Source:** *Yiyong Shengwu Lixue/Journal of Medical Biomechanics*, v 27, n 4, p 438-443+450, August 2012 **Language:** Chinese
Database: Compendex
Accession number: 20125015795351

17. **An experimental study of effects of active-heating-system for extravehicular spacesuit gloves on working performance**
Ding, Li; Han, Long-Zhu; Yang, Chun-Xin; Yang, Feng; Yuan, Xiu-Gan
Source: *Hangtian Yixue Yu Yixue Gongcheng/Space Medicine and Medical Engineering*, v 18, n 1, p 47-51, February 2005 **Language:** Chinese
Database: Compendex
Accession number: 2005139014857

18. **Research of biomechanical evaluation methods of hand performance fatigue.**
Ding, Li; Yang, Feng; Chen, Shou-Ping; Yang, Chun-Xin; Yuan, Xiu-Gan
Source: *Hangtian Yixue Yu Yixue Gongcheng/Space Medicine and Medical Engineering*, v 19, n 5, p 363-367, October 2006 **Language:** Chinese
Database: Compendex
Accession number: 20065110317704

19. **Research on the human thermal model with a poly-segmented hand**
Ding, Li (Bioengineering Department, Beihang University, Beijing 100083, China); Sang, Minjing; Lei, Yanpeng; Yuan, Xiugan **Source:** *Heat Transfer - Asian Research*, v 37, n 2, p 94-100, March 2008
Database: Compendex
Accession number: 20081211150801

20. **Ergonomics implications of extravehicular activity spacesuit glove**
Ding, Li (School of Aeronautic Science and Technology, Beijing University of Aeronautics and Astronautics, Beijing 100083, China); Yang, Feng; Yang, Chunxin; Yuan, Xiugan **Source:** *Beijing Hangkong Hangtian Daxue Xuebao/Journal of Beijing University of Aeronautics and Astronautics*, v 31, n 4, p 416-420, April 2005 **Language:** Chinese
Database: Compendex
Accession number: 2005249160719

21. **Investigation on ergonomics characteristics of protective clothing based on capture of three-dimensional body movements**
Hu, Imin (School of Aeronautic Science and Technology, Beihang University, Beijing 100083, China); Ding, Li; Yang, Chunxin; Yuan, Xiugan
Source: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 4561 LNCS, p 856-864, 2007, *Digital Human Modeling - First International Conference on Digital Human Modeling, ICDHM 2007. Held as Part of HCI International 2007, Proceedings*
Database: Compendex

Accession number: 20080411041834

22. **Study on the appraisal methods of hand fatigue**
Ding, Li (Bioengineering Department, BeiHang University, Xueyuan Road 37#, Beijing 100083, China); Yang, Feng; Yang, Chunxin; Yuan, Xiugan; Li, Yang **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 4561 LNCS, p 33-41, 2007, *Digital Human Modeling - First International Conference on Digital Human Modeling, ICDHM 2007. Held as Part of HCI International 2007, Proceedings*
Database: Compendex
Accession number: 20080411041748

23. **Thermal physiology of hand under cold environment**
Ding, Li (Bioengineering Department, Beihang University, Beijing 100083, China); Yang, Feng; Lei, Yan-Peng; Yang, Chun-Xin; Yuan, Xiu-Gan **Source:** *Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics*, v 28, n 6, p 1007-1009, November 2007 **Language:** Chinese
Database: Compendex
Accession number: 20074810951772

文献引用检索证明

作者姓名：丁立(Ding，Li)

经检索“Web of Science 引文索引数据库”，该作者发表的 1 篇论文，他引 2 次(in SCIE&CPCI-S)。

（他引定义：引用文献中不包含被检索作者的引用视为他引。）

检索结果见附件，共 1 页。

检索时间为 2016 年 5 月 19 日。

特此证明！

证明人（签字）：惠瑶

证明单位（盖章）：北京航空航天大学图书馆

二〇一六年五月十九日

附件：

1. Study on functional relationships between ergonomics indexes of manual performance
作者: Hu, Hui-Min; Ding, Li; Chen, Shou-Ping; 等.
会议: 16th IAA Humans in Space Symposium 会议地点: Beijing, PEOPLES R CHINA 会议日期: MAY 20-24, 2007
会议赞助商: Int Acad Astronaut
ACTA ASTRONAUTICA 卷: 63 期: 7-10 页: 811-821 出版年: OCT-NOV 2008
Web of Science 核心合集中的 "被引频次": 3

他引 2 次：

1. Feasibility of teleoperations with multi-fingered robotic hand for safe extravehicular manipulations
作者: Saggio, Giovanni; Bizzarri, Mariano
AEROSPACE SCIENCE AND TECHNOLOGY 卷: 39 页:666-674 出版年: DEC 2014

2. Electrical stimulation during skill training with a therapeutic glove enhances the induction of cortical plasticity and has a positive effect on motor
作者: Christova, Monica; Rafolt, Dietmar; Golaszewski, Stefan; 等.
BEHAVIOURAL BRAIN RESEARCH 卷: 270 页: 171-178 出版年: AUG 15 2014

2016年专业技术职务评聘论文发表及收录情况证明表

单位：生物与医学工程学院

姓名	丁立	工作证号	07441	现任职称	副教授	任职时间	2002.9

现职以来发表论文及收录情况：收录类别、作者贡献（第一、通讯等）仅计算1次；论文收录以图书馆检索证明为准，未检索到的来源刊论文仅计算1篇

类别	合计	SCI	SSCI	CSSCI	EI	ISTP	中文核心期刊	其他
一、符合职称申报条件论文	42	7	1		22		10	2
其中：1. 第一作者	18	3			8		5	2
2. 学生第一本人第二作者	5	1			4			
3. 通讯作者	19	3	1		10		5	
二、其他								国防报告

本人承诺以上所填属实，如与事实不符，本人愿承担一切责任。

本人签字：丁立　　　　日期：2016 年 5 月 19 日

单位负责人签字（加盖公章）：[signature]　　　　日期：2016 年 5 月 19 日

北京航空航天大学 生物与医学工程学院 1100000173845

图书馆意见：

~~经检索，上表所列论文发表及收录情况属实~~。

经检索，上表中被SCIE、SSCI、EI数据库收录的文章数量情况属实。

北京航空航天大学 图书馆 检索专用章

证明人：惠瑶　盖章：　　　　日期：2016 年 5 月 19 日

注：1.申请人认真如实填写相关信息后A4纸单面打印；

2. 对于学生第一本人第二作者的论文需填写《2016年专业技术职务评聘研究生指导情况证明表》由所在单位认定，主管副院长签字，学院盖章，研究生院审定，一并去图书馆认定。

用章审批材料.[illegible]

北京航空航天大学专业技术职务评审
任现职以来主要教学工作业绩水平证明表

姓　　名＿＿丁立＿＿　　　　单位＿＿生物与医学工程学院＿＿

现任专业技术职务＿＿副教授＿＿　　　　任现职时间＿＿2002.8＿＿

申请专业技术职务＿＿教授＿＿　　　　填表日期＿＿2016.5.20＿＿

一、教学总体情况

任现职以来，独立指导硕士研究生＿10＿届＿18＿人，其中毕业＿11＿人，在读＿7＿人；指导本科毕设＿25＿人，主讲本科生课＿6＿门，其中必修课＿5＿门；主讲研究生课＿2＿门、其中学位课＿2＿门。年均授课＿108＿学时。

二、本科教学工作量

	课程代码	课程名称	学年-学期	课程学时	本人授课学时	授课对象（本科生/留学生等）	授课次数（几轮次）	课程性质
教学工作量	10Z80190	人体工效学	2005-2015-2	48	40	本科生/留学生	11	必修
	F10C3441	高级热体工效学	2016-1	32	26	本科生	1	必修
	10Z80030	连续介质力学	2005-2014-1	68	34	本科生	9	必修
	G10C4430	专业综合实验	2006-2016-1	40	40	本科生	7	必修
	E10B2291	人体工效学导论	2015-2016-2	16	10	本科生	2	专业基础核心
	B2G100140	人体工效学	2014-2016-1	16	12	本科生	3	公共选修

注：课程性质为校级核心、专业基础核心、专业方向核心、必修、选修、公共选修等。

院(系)确认人签字：

教务处确认人签字：

<table>
<tr><td rowspan="3">教学含成教果材奖</td><td>获奖时间</td><td colspan="2">获奖项目名称</td><td>获奖等级</td><td>本人排名</td></tr>
<tr><td>2010</td><td colspan="2">“成飞”奖教金</td><td>二等奖</td><td>1</td></tr>
<tr><td>2009</td><td colspan="2">开放式创新性“生物（医学）工程专业综合实验”课程的教学改革与实践</td><td>校级二等奖</td><td>3</td></tr>
<tr><td rowspan="6">教学研究</td><td>起止时间</td><td>教改立项项目名称（含编写教材、讲义）</td><td>项目来源</td><td>完成情况</td><td>本人作用</td></tr>
<tr><td>2015-2016</td><td>人体工效学</td><td>工信部“十二”规划教材</td><td>出版</td><td>1</td></tr>
<tr><td>2011.1-2013.12</td><td>人体工效学</td><td>北航精品课</td><td>完成</td><td>2</td></tr>
<tr><td>2015.6-2016.5</td><td>基于 WEB 技术的教学模式探讨</td><td>教改</td><td>完成</td><td>1</td></tr>
<tr><td>2007.9-2010.9</td><td>开放式创新性“生物工程专业综合实验”课程的教学改革与实践</td><td>教改</td><td>完成</td><td>5</td></tr>
<tr><td>2012</td><td>《人体工效学》研究型实验教学探索与实践</td><td>高校实验室工作研究</td><td>发表</td><td>1</td></tr>
</table>

其它	任务完成情况（含辅导员、军训、学生工作论文、指导青年教师及青年技术人员社会实践等）	本人作用
	指导 3 名学生获得国家大学生创新性实验计划项目“基于工效学的办公室风水合理性研究”资助 1.0 万元，（2015.4~2016.4）。已有 1 篇论文被 EI 收录的国际会议录用。	指导
	指导 3 名学生获得 SRTP 项目“基于特殊环境下飞行员的认知工效评价方法研究”资助 0.2 万元（2013.4~2014.4）。发表有 2 篇国际会议论文，1 篇国内会议。获得冯如杯二等奖（2014.5）	指导
	指导 2 名学生获得国家大学生创新性实验计划项目“基于 ANYBODY 的航天员上肢训练方案筛选”资助 1.0 万元，（2012.4~2013.4）。已有 1 篇论文被 EI 录用。获得冯如杯二等奖（2013.5）	指导
	指导 4 名学生“医疗超声探头的人因工程学设计及评价”项目，获得冯如杯二等奖（2011.5）。	指导
	指导 3 名学生获得 SRTP 项目“热防护劳保手套热特性测试技术研究”资助 0.2 万元，（2009.1-2010.12）。	指导
	指导 4 名学生获得北京大学生创新性实验计划项目“航天员超低温抓握力测试仪器研究”资助 0.9 万元，（2008.12-2009.12），获得发明专利 1 项，获得冯如杯二等奖。	指导
	已指导 11 届 22 名本科生毕业设计（其中 1 名校优，2 名系优），本年度又指导 3 名本科毕业设计。	指导

徐烈情

院(系)确认人签字：

教务处确认人签字：

本人确认表内所填内容属实　　签名：

院(系)确认人签字（公章）：

教务处确认盖章：

日期：

北京航空航天大学生物与医学工程学院 1100000173845

北京航空航天大学 教务处

三、研究生教学工作量

	课程名称	起止时间	课程学时	本人授课学时	授课对象（研究生/留学生等）	授课次数（几轮次）	课程类型
教学工作量	人体工效学及康复工程	2006.3-至今	48	40	硕士研究生	10	学位
	人体工效学及康复工程实验	2011.3-至今	16	4	硕士研究生	6	学位
	生物医学工程和生物工程导论	2006.3-2011.3	18	2	文科硕士研究生	7	选修
	生物与医学工程概论	2006.3-2011.3	60	4	硕士研究生	7	学位
	生物医学工程学科综合课	2007.3-2011.3	48	4	博士研究生	6	学位

院(系)确认人签字：李桃

研究生院确认人签字：郑浓梅

教学成果奖（含教材）	获奖时间	获奖项目名称	获奖等级	本人排名

	时间	项目名称	项目来源	完成情况	本人作用
教学研究	2011.4-2015.11	人体工效及康复工程	北航研究生精品课	完成	1
	2015.6-2015.12	手机的显控界面工效学评价	研究生教学案建设项目	完成	1
	2011.10-2012.10	连续性研究型实验教学方法研究	研究生教育发展专项基金	完成	2
	2012	启发式教学在《人体工效学》专题讨论中的应用	高校实验室工作研究	发表	1

冯秀娟

彭晓霞

	任务完成情况（含辅导员、学生工作论文、指导青年教师及青年技术人员社会实践等）	本人作用
其它	作为副导师指导毕业北航博士 1 名（呼慧敏），目前协助指导北航博士研究生 2 名（李先学，田寅生），作为导师指导毕业北航硕士 11 名（岳国栋，刘何庆，张春光，李晶，田寅生，薛立豪，李静文，杨涛，李倬有，刘畅，马德良），目前指导北航硕士研究生 7 名（杜浩，周建强，张静，叶青，陈尧，罗恢育，徐莹）。	导师

宋聪

院(系)确认人签字：李桃

研究生院确认人签字：

本人确认表内所填内容属实　签名：丁立

院(系)确认人签字（公章）：李桃

研究生院确认人签字（公章）：

日期：

北京航空航天大学 生物与医学工程学院 1100000173845

北京航空航天大学 研究生院 1100000202015

2016年专业技术职务评聘专利与获奖情况认定表

单位	生物与医学工程学院	姓名	丁立	工作证号	07441	任职时间	2002.9

获批专利情况

现职以来以第一享有人（含学生第一本人第二）名义共授权专利 5 项；任现职以来共获得已授权专利况：

类 别	专利数	发明专利	实用新型	外观设计
第一享有人	5	5		
数量	5	5		

序号	专利名称	专利类型	授权日期	批准机构	专利号	仅限首次授权		
						权利单位	人数	本人排名
1	低压防护手套灵活性测试装置	发明专利	2014.12	国家知识产权局	ZL 2012 1 0570139.0	北京航空航天大学	7	2(学生第1)
2	超低温恒温抓握棒装置	发明专利	2013.04	国家知识产权局	ZL 2010 1 0184103.X	北京航空航天大学	2	1
3	低温有压手套作业能力测试装置	发明专利	2012.12	国家知识产权局	ZL 2009 1 0244608.8	北京航空航天大学	2	1
4	超低温抓握力测试装置	发明专利	2011.05	国家知识产权局	ZL 2009 1 0084751.5	北京航空航天大学	5	1
5	封闭式含冰晶颗粒气体生成装置	发明专利	2011.07	国家知识产权局	ZL 2009 1 0090316.3	北京航空航天大学	4	1
6								
7								
8								

人承诺以上所填属实。

承诺人：丁立　　　学院审核人（盖章）：楚春青

研部门审核意见：

经审核，上表所列奖项中，符合首次授权状态的归档专利共 5 项（序号：1-5）。

审核人：郝雷阳 2016.5.23　盖章：

2.获奖情况

任现职以来获得国家级教学/科研成果奖__项；省部级教学/科研成果一等奖前五名、二等奖前三名或三等奖第一完成人共__1__项。请填写任现职以来获得教学、科研、管理奖励情况。

序号	奖励名称	颁奖部门	奖励级别	获奖时间	人数	本人排名
1	EVA手套热特性测试装置研制(09-X-013)	北京航空航天大学	北航科技进步二等奖	2010	10	1
2						
3						
4						
5						
6						

本人承诺以上所填属实。

承诺人：[illegible]　　学院审核人（盖章）：[illegible]

科研部门审核意见：

经审核，上表所列奖项中，情况属实的国家级科研成果奖__0__项（序号:0），省部级科研成果__0__项（序号:0）。

审核人：[illegible]　　盖章：

注：1.申请人认真如实填写相关信息后A4纸单面打印；
2.申请人签字确认后将此表及相关证明材料交至所在学院，由学院统一送至科研院审核；
3.申请人填写申报材料时以审核后的信息为准。

课题信息查询

费负责人：丁立　　　　工作证号：07441　　　　查询范围：2002-10-01到2016-05-20

实到经费：848.35　　　　单位：万元

号	经费号	项目名称	项目来源	实到经费	设备费	外协费	课题性质	项目负责人
1	54-4777-01	空天全压服耐及热舒适计算	航宇救生装备有限公司	9	0	0	技术开发	丁立
2	52-7125-01	舰船使用与维修多人协作任务仿真及评价技术研究	中国船舶重工集团公司第七零一研究所	35	0	15	技术服务	丁立
3	52-7139-01	科研项目	中国人民解放军63919部队	5	0	0	技术服务	丁立
4	38-0862-01	科研项目	中国航天员科研训练中心	5.6	0	0	非51合同	丁立
5	54-4118-01	人体睡眠体压分布参数辅助测试评价研究	中国标准化研究院	7	0	0	技术服务	丁立
6	52-6989-01	科研项目	航宇救生装备有限公司	8	0	0	技术开发	丁立
7	03-2213-01	试验通道内液态水含量测试技术深入研究	中国航空工业集团公司沈阳发动机设计研究所	17	0	4	非51合同	丁立
8	54-4023-01	充液抗荷技术过载响应特性仿真研究	航宇救生装备有限公司	5	0	0	技术开发	丁立
9	52-6162-01	低压大气环境对流换热水平研究	北京卫星环境工程研究所	5	0	0	技术服务	丁立
0	34-0338-01	显控界面工效学仿真测评技术和标准研究	国家质量监督检验检疫总局	356	28	39	非51合同	丁立
1	32-2547-01	城市公共交通设施无障碍设计指南	国家标准化管理委员会	7.5	0	0	非51合同	丁立
2	32-2546-01	城市公共交通设施工效学设计指南	国家标准化管理委员会	7.5	0	0	非51合同	丁立
3	54-3294-01	50百分位成年男性胸腹部三维有限元模型建立和碰撞损伤机理研究	中国标准化研究院	8	0	0	技术服务	丁立
4	54-3164-01	城市公共基础设施宜人性调研和工效学测评	中国标准化研究院	10	0	0	技术服务	丁立
5	52-7244-01	科研项目	中国人民解放军航天员科研训练中心	20	0	0	技术开发	丁立
6	52-5688-01	舱内连接器操作空间试验平台工装研制	航天员科研训练中心	18	0	0	技术开发	丁立
7	52-4902	科研项目	中国航天员科研训练中心	16	0	0	技术开发	丁立
8	52-4574	囊式代偿服工效学评价试验	中国人民解放军空军航空医学研究所	4.948	0	0	技术服务	丁立

19	37-6307	脑-手系统作业的生物力学机理研究	国家自然基金委	2	0	0	非51合同	丁立
20	52-6145	科研项目	航天院科研训练中心	20	3.1312	11.8688	技术开发	丁立
21	52-3834	科研项目	航天院科研训练中心	20	0	0	技术开发	丁立
22	52-3646	颈部防护装置试验件的设计制作	中国人民解放军空军航空医学研究所	1.5	0	0	技术开发	丁立
23	52-3086	科研项目	中国航天科技集团公司第一研究院	20	0	0	技术服务	丁立
24	54-1806	基于典型应用的工效学实验组织和招募	中国标准化研究院	15	0	0	技术服务	丁立
25	37-5360	基于人—手套系统的舱外航天服手套工效研究	国家自然科学基金	58	4.488	3	非51合同	丁立
26	30-1331	基于人—手套系统的舱外服手套工效研究	工信部："唯实"人才培育基金	1	0	0	非51合同	丁立
27	52-1336	人体热负荷试验	空军航空医学院研究所	2	0	0	技术服务	丁立
28	52-1200	座舱压力制度与防护方式仿真模型	空军航空医学研究所	8	0	0	技术服务	丁立
29	54-0609	滑移边界流场计算研究	中国科学院声学研究所	8	0	0	技术服务	丁立
30	54-0319	车辆座椅舒适性测试	中国标准化研究院	1.6	0	0	技术开发	丁立
31	52-0971	俄罗斯尿液收集装置研究	航宇救生装备有限公司	5	0	0	技术开发	丁立
32	52-0580	舱外作业手操纵能力测试平台	航天医学工程研究所	14	0	0	技术开发	丁立
33	52-0535	座椅舒适性评价实验协作	中国人民解放军空军航空医学研究所	6	0	0	技术服务	丁立
34	54-0260	耐高温手套标准研究	佛山市南海天龙亿达事业有限公司	8	0	0	技术服务	丁立
35	51-8369	科研项目	解放军空间航空医学研究所	5	0	0	技术服务	丁立
36	51-8227	舱外夫手套德热防护试验研究	总装航天医学工程研究所	4	0	0	技术开发	丁立
37	51-7708	高温环境下人体作业能力工效试验	中国人民解放军空军航空医学院研究所	2.3	0	0	技术服务	丁立
38	51-7632	人体对座椅座面和靠背的压力分布测量*	中国人民解放军空军航空医学研究所	5	0	0	技术开发	丁立
39	51-7336	典型手动操纵装置工效测试平台研制及试验验证	总装航天医学工程研究所	3	0	0	技术开发	丁立
40	03-1804	防冰系统实验技术研究与验证	中航一集团沈阳发动机设计研究所	36.4	8	16	非51合同	杨春信

学科学技术研……章（5-

41	51-6040	"手套热特性测试装置研制"	总装备部航天医学工程研究所	36	3	13	技术开发	丁立
42	37-2971	科研项目	国家基金	22	0	0	非51合同	丁立

科学技术研究院

查询日期：2016年05月20日

究院

3)

为表彰在促进我校科学技术进步工作中作出突出贡献者，特颁此证，以资鼓励。

获奖项目：EVA手套热特性测试装置研制

获 奖 者：丁立、席林斌、袁修干、李潭秋、谢广辉、雷岩鹏、王超、李猛、崔希灵、贾香兰

获奖等级：二等奖

证 书 号：09—X--013

北京航空航天大学

2009年12月25日

荣誉证书

HONORARY CREDENTIAL

北京航空航天大学教学成果奖

获 奖 证 书

获奖成果：开放式创新性“生物（医学）工程专业综合实验”课程的教学改革与实践

获 奖 者：赵峰、蒲放、丁立、牛海军、胡青华

获奖等级：二等

北京航空航天大学

二〇〇九年九月

（颁证部门钢印）

姓　　名　丁立

性　　别　男

出生年月　1971年03月

工作单位　昆明理工大学

专业名称　交通工程

资格名称　副教授

评审组织　云南省中青年破格晋升高级职务评审委员会

资格认定时间　2002年08月07日

发证时间　2003年01月13日

证书编号：170107510

博士研究生

毕业证书

中华人民共和国教育部制

No. 00015121

研究生 丁 立 性别 男 ，一九七一 年 三 月 十六 日生，于 一九九七 年 九 月至 二零零零 年 九 月在 人机与环境工程 专业学习，学制 三 年，修完博士研究生培养计划规定的全部课程，成绩合格，毕业论文答辩通过，准予毕业。

校(院、所)长：沈士团

培养单位：北京航空航天大学

二零零零 年 九 月 三十 日

编号：97004587

丁立　系云南楚雄

人，一九七一年三月

十六日生。在我校人机

与环境工程学科（专业）已通过

博士学位的课程考试和论文答辩，成

绩合格。根据《中华人民共和国学位

条例》的规定，授予工学博士

学位。

北京航空航天大学
校长　沈士团

学位评定委员会主席　沈士团

二〇〇〇年十一月二十四日

证书编号 100062000656

博士后证书

丁立 博士于二〇〇二年十月至二〇〇四年十二月在北京航空航天大学 力学 学科从事博士后研究工作，并完成在站期间的科研任务。

特发此证

全国博士后管理委员会

主 任：徐颂陶

二〇〇四 年 十二 月 十四 日

编 号：16161

留学回国人员证明

（2012）组 教 （文） 证字1072号

兹证明 丁立 男☑、女☐，系我国在 美 国，

CORNELL UNIVERSITY
康奈尔大学 学校（单位）的高级研究学者☐、访问学者☑、

博士后☐、博士研究生☐、硕士研究生☐、本科生☐、大专生☐、其他留学人员☐

护照号码 G48452737 发照机关 中国公安部出入境管理局

在我驻外使（领）馆报到日期 2011年 05月 09日

注册入学（工作）日期 2011年 05月 09日

毕（结）业、工作结束日期 2012年 05月 08日

毕（结）业证书名称 号码

回国（拟）工作单位：北京航空航天大学

附：毕（结）业证书复印件。

留学回国人员签字：

教育（文化）处（组）
经 办 人 签 字：

教育（文化）处（组）公章

教育（文化）处（组）
负 责 人 签 字：

2012年03月21日

第一联：交留学回国人员

教育部国际合作与交流司 2004 年制表

注 意 事 项

1.本证明只为学成回国工作的留学人员开具。

2.本证明由我驻外使（领）馆教育（文化）处（组）在留学人员回国时填写，不得涂改。

3.本证明经使（领）馆教育（文化）处（组）经办人、负责人签字并在第一、第二联加盖公章方为有效。

4.第一联由留学人员保存，其他单位可查验原件，收存复印件，不得收取原件。

G48452737

VISA

UNITED STATES OF AMERICA

Issuing Post Name
BEIJING
Surname
DING
Given Name
LI
Passport Number
G48452737
Entries
M
Annotation
N0007976173
P-1-00043
212 (E) TWO YEAR RULE APPLIES

Control Number
20110887770001
Visa Type/Class
R 31
Sex
M
Birth Date
16MAR1971
Nationality
CHIN
Issue Date
30MAR2011
Expiration Date
28MAR2012
0100

E11193139

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G484527372CHN7103162M1203288J1BEJOUMW6301042

结 业 证 书

学员 丁立，男，1971 年 3 月 16 日出生，于二〇一〇年九月至二〇一一年一月在教育部直属北京语言大学出国留学人员培训部接受英语培训。经国家留学基金管理委员会统考，成绩及格，准予结业。

北 京 语 言 大 学
出国留学人员培训部
二〇一一年一月

北语培证字第 1101240 号

CERTIFICATE

It is hereby certified that Mr.**Ding Li**, born on March 16, 1971, took the **Advanced** English Training Program at the Pre-departure Training Department, BLCU, affiliated with the Ministry of Education, from Sep. 2010 to Jan. 2011, and has passed the required tests with satisfactory scores.

The Department for Pre-departure Training
Beijing Language and Culture University
Issued in Jan. 2011

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国家公派留学人员

英语培训成绩单

学员 丁立 于二〇一〇年九月至二〇一一年一月在我部参加英语培训，并参加国家留学基金管理委员会统考。成绩如下：

项目	成绩
听力 （满分 40）	**20**
阅读 （满分 40）	**28**
写作 1 （满分 15）	**11**
写作 2 （满分 25）	**16**
口语 （满分 30）	**19**
平时成绩与考勤 （10 分）	**10**
总成绩 （满分 160 分）	**104**

北京语言大学
出国留学人员培训部
二〇一一年一月

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聘　　书

兹聘请　丁立　为中国航空学会人体与环境工程专业委员会（青年）委员。

中国航空学会航空机电、

人体与环境工程专业委员会

二零一三年十一月

证　　明

兹有北京航空航天大学生物与医学工程学院丁立同志为中国航天员科研训练中心人因工程国防科技重点实验室基础研究基金专家组成员，聘期为 2012 年 12 月至 2016 年 12 月。

特此证明。

人因工程国防科技重点实验室

2016 年 5 月 19 日

证　明

北京航空航天大学：

2014 年 10 月，贵单位研制的暖体假手测试装置交付我中心，应用于新型航天服手套的热特性测试，性能稳定，其应用技术在国内处于领先水平。

特此证明。（此证明仅用于该课题组人员职称评定使用）

中国人民解放军

航天员科研训练中心科技处

二〇一六年五月二十七日

应用证明

项 目 名 称	头盔通风散热仿真分析及验证试验技术研究
应 用 单 位	航宇救生装备有限公司
通 讯 地 址	湖北省襄阳市新华北路 29 号航宇救生装备有限公司
应用成果起止时间	2015 年 4 月—至今
经 济 效 益 （万元）	
年 度	2015 年
新增产值（产量）	480 顶
新增利税（纯收入）	1.2 万
年增收节支总额	576 万

应用情况及社会效益：

该仿真和实验数据的成果对于我国新型飞行员头盔的热设计有重要指导意义。

该研究通过仿真和试验验证的方法对新型头盔在不同环境下的头盔温度场变化、头部温度变化、头盔的不同通风水平热防护能力等的研究成果即将应用于某重点型号上，对新型飞行员头盔的热舒适性设计提供了技术支撑，同时也为新型飞行员头盔后期实物的实验和测试打下了良好的基础。

航宇救生装备有限公司

个体防护技术研发部

应用证明

项 目 名 称	充液抗荷技术过载响应特性仿真研究
应 用 单 位	航宇救生装备有限公司
通 讯 地 址	湖北省襄阳市新华路 29 号
应用成果起止时间	2015 年 10 月—至今
经 济 效 益 （万元）	
年 度	2016 年
新增产值（产量）	600 万元
新增利税（纯收入）	80 万元
年增收节支总额	

应用情况及社会效益：

该仿真结果已应用于指导我国新型飞行员个体防护服的研制。

该仿真所计算的充液抗荷服在不同过载下的服装力学、上下肢力学变化，及服装和肌肉变形数据，以及所提出的服装设计建议在新型充液抗荷服的设计中得到应用，同时也为新型充液抗荷服后期的试验测试打下了良好的基础。

航宇救生装备有限公司 个体防护技术研发部

应用证明

项 目 名 称	舱外航天手套热特性测试平台研制
应 用 单 位	总装备部司令部作战试验局
通 信 地 址	北京市北三环中路 4 号（100720）
应用起止时间	2007 年 7 月——2008 年 10 月
经济效益（万元）	
年　　度	
新增产值（产量）	
新增利税（纯收入）	
年增收节支总额	

应用情况及社会效益（不超过 500 个汉字）

该项目取得的成果已被应用于“神舟 7 号”任务飞天舱外航天手套的研制。

该平台在进行飞天舱外航天手套测试的过程中性能稳定，满足了热防护和操作工效测试要求，保障了飞天舱外航天手套研制工作的顺利开展，在飞天舱外航天手套的研制过程中发挥了重要作用。该平台为我国后续舱外航天手套热特性和工效学实验研究打下了良好的基础。

总装备部司令部作战试验局（盖章）

年　　月　　日

应用证明

项目名称	基于Web模式的空间站工效学评价信息管理系统研制
应用单位	中国航天员科研训练中心人因工程国防科技重点实验室
通讯地址	北京市海淀区北清路26号
应用成果起止时间	2014年10月—至今
经济效益（万元）	
年度	
新增产值（产量）	
新增利税（纯收入）	
年增收节支总额	

应用情况及社会效益：

该工效学评价信息管理系统已被应用于空间站工效学评价信息管理。

该系统在空间站舱载产品的工效学评价和管理使用过程中性能稳定，满足空间站产品的工效学评价、信息采集、数据分析和信息管理等的需求和工作要求。在空间站舱载产品的工效学评价和管理发挥了重要作用。该系统为我国后续空间站舱载产品的工效研究和评价提供了良好的基础。

（盖章）

人因工程国防科技重点实验室

年 月 日

应用证明

项 目 名 称	舱外作业手操作能力测试系统
应 用 单 位	中国航天员中心人因工程国防科技重点实验室
通 讯 地 址	北京市海淀区北清路 26 号
应用成果起止时间	2010 年 10 月至今
经济效益（万元）	
年度	
新增产值（产量）	
新增利税（纯收入）	
年增收节支总额	

应用情况及社会效益：

该测试平台已被应用于我国航天员人群手操作能力测试研究。

该平台在航天员人群戴舱外服手套的操作能力测试过程中性能稳定，满足航天手套测试舱的环境和工作要求，获取了戴舱外航天服手套手操作能力的数据，在舱外航天手套的工效评价过程中发挥了重要作用。该平台为我国后续舱外航天手套的工效学研究和评价打下了良好的基础。

人因工程国防科技重点实验室

应 用 证 明

项 目 名 称	EVA 手套热特性测试装置研制
应 用 单 位	总装备部航天医学工程研究所
通 讯 地 址	北京海淀区北清路 26 号院
应用成果起止时间	2007 年 6 月至今
经 济 效 益 (万 元)	
年 度	
新增产值(产量)	
新增利税（纯收入）	
年增收节支总额	

应用情况及社会效益:

飞天舱外航天服手套（简称 EVA 手套）是飞天舱外航天服的重要组成部分，在－120℃~＋120℃温度环境下的热防护技术是 EVA 手套研制中的关键技术之一。“EVA 手套热特性测试装置”是 “神舟七号” 任务 EVA 手套进行热防护性能测试必备的专用设备。该装置能够快速建立－130℃~＋130℃的温度环境，测试 EVA 手套在地面模拟出舱活动状态下的热防护性能。

该装置保障了 EVA 手套研制工作的顺利开展，在 EVA 手套的研制过程中发挥了重要作用，为“神舟七号”任务的顺利完成作出了贡献。该装置还将继续用于我国后续 EVA 手套的热特性和工效测试研究。

应用情况表明，该装置功能完善，有精确的超高低温和压力控制能力，可实现多点温度的实时采集，有较强的数据处理能力，人机界面友好。

航天医学工程研究所

应用单位（盖章）

年 月 日

应用证明

项 目 名 称	飞行员个体防护装备温度测试系统
应 用 单 位	中国人民解放军空军航空医学研究所
通 讯 地 址	北京市海淀区阜成路 28 号
应用成果起止时间	2012 年 4 月至今
经济效益（万元）	
年度	
新增产值（产量）	
新增利税（纯收入）	
年增收节支总额	

应用情况及社会效益：

该系统已被应用于我国新型歼击机飞行员个体防护装备的热特性测试研究。

该系统在飞行员个体防护装备的热特性测试过程中性能稳定，满足飞行员个体热防护测试的环境和工作要求，保障了新式个体防护装备研制工作的顺利开展，在最新的装备测试过程发挥了重要作用。该系统为后续新型飞行员个体防护装备的热特性研究打下了良好的基础。

全国人类工效学标准化技术委员会
文　　件

SAC/TC 7　　　　　　　　　　　　　　　　2014 第 20 号

关于报批《日用产品的易操作性 第 1 部分：针对使用情境和用户特征的设计要求》等五项国家标准的函

国家标准化管理委员会：

根据你委员会 2012 年和 2013 年制修订国家标准计划（项目编号：20132306-T-469、20132307-T-469、20120396-T-469、20130246-T-469、20130247-T-469），我标准化技术委员会完成了下列国家标准修订工作，现报上，请审批、编号、发布。

推荐性标准：

1、《日用产品的易操作性 第 1 部分：针对使用情境和用户特征的设计要求》（GB/T××××.1-××××）；

2、《消费类产品和公用类产品的可用性　第 2 部分：总结性试验方法》（GB/T××××.2-××××）；

3、《人-系统交互工效学第 307 部分:电子视觉显示器的分析和符合性试验方法》（GB/T 18978.307-××××）

4、《城市公共交通设施工效学设计指南》（GB/T××××

-××××）

5、《城市公共交通设施无障碍设计指南》（GB/T××××-××××）

建议以上标准于2015年8月1日起实施。

全国人类工效学标准化技术委员会

业务专用

二零一四年十二月二十八日

ICS 13.80
A 25

中华人民共和国国家标准

GB/T××××—201×

城市公用交通设施无障碍设计指南

Accessibility design guide for urban public transport facilities

（报批稿）

（本稿完成日期：2015-7-9）

××××-××-××　　　　　　××××-××-××

中华人民共和国国家质量监督检验检疫总局
中 国 国 家 标 准 化 管 理 委 员 会　发布

目　录

前　　言

本标准按照GB/T 1.1- 2009给出的规则起草。

本标准由全国人类工效学标准化技术委员会（SAC/TC 7）提出并归口。

本标准起草单位：北京航空航天大学、中国标准化研究院、厦门欣诚通物流有限公司、建设部标准定额所、北京市交通标准化技术委员会、交通部公路科学研究院、广东警官学院、云南交通职业学院。

本标准主要起草人：丁立、呼慧敏、赵朝义、赵鑫、林华兴、黄金屏、安小芬、姜明、张勇刚、尤海波、易赛岚、冉令华、刘太杰、张欣、张运红、罗玲。

城市公用交通设施无障碍设计指南

1　范围

本标准规定了城市公用交通设施无障碍设计原则和工效学参数使用原则,同时给出了主要公用交通设施无障碍设计原则。

本标准适用于城市公用交通设施及类似设施的无障碍设计和评价。

2　规范性引用文件

下列文件对于本文件的应用是必不可少的。凡是注日期的引用文件，仅所注日期的版本适用于本文件。凡是不注日期的引用文件，其最新版本（包括所有的修改单）适用于本文件。

GB/T 10001.9-2008 标志用公共信息图形符号—第9部分：无障碍设施符号
GB/T 12985-91 在产品设计中应用人体尺寸百分位数的通则
GB/T 13547-92 工作空间人体尺寸
GB 14887-2011 道路交通信号灯
GB/T 15565.2-2008 图形符号 术语 第2部分:标志及导向系统
GB/T 20002.2-2008 标准中特定内容的起草 第2部分：老年人和残疾人的需求
GB/T 31054-2014 公共信息导向系统 基于无障碍需求的设计与设置原则
GB 50642-2011 无障碍设施施工验收及维护规范
GB 50763-2012 无障碍设计规范
DB11/T 805-2011 人行天桥与人行地下通道无障碍设施设计规程

3　术语与定义

GB 50763、GB/T 12985、GB/T 15565、GB/T 20002.2界定的以及下列术语和定义适用于本文件。为了便于使用，以下重复列出了GB 50763、GB/T 20002.2中的某些术语和定义。

3.1

无障碍设计 accessible design

此类设计注重将标准设计扩展到具有某些机能缺陷的特殊人群,通过下列方法最大限度地增加易于使用产品、建筑物或服务的潜在客户的数量。

—设计让大多数使用者无需任何修改就能很容易地使用产品、服务和环境;

—让产品或服务适合不同使用者（用户适配接口）;

—设有标准化接口，以便能与残疾人专用产品兼容。

[GB/T 20002.2-2008，定义3.2]

3.2

盲道 tactile ground surface indicator

在人行道上或其他场所铺设的一种固定形态的地面砖，使视觉障碍者产生盲杖触觉及脚感，引导视觉障碍者向前行走和辨别方向以达到目的地的通道。

[GB/T 50763-2012，定义2.0.2]

3.3

无障碍设施 barrier-freefacilities

为残疾人、老年人等社会特殊群体自主、平等、方便地出行和参与社会活动而设置的进出道路、建筑物、交通工具、公共服务机构的设施以及通信服务等设施。

[GB 50642-2011,定义2.0.1]

3.4

无障碍出入口 Accessible entrance

在坡度、宽度、高度上以及地面材质、扶手形式等方面方便行动障碍者通行的出入口。

[GB 50763-2012,定义2.0.5]

3.5

盲文铭牌 Braille board

在无障碍设施或附近的固定位置上设置的采用盲文标识告知信息的铭牌。

[GB 50642-2011,定义2.0.6]

4 设计原则

城市公用交通设施设计时应综合考虑机能障碍者的生理、心理特点及使用需求与习惯偏好等因素，使城市公用交通设施的功能和要求与这些人群的身体特征和使用需求相适应。

在使用工效学参数进行无障碍设计时，可参考城市公用交通设施工效学设计指南中规定的参数使用原则。

5 主要公用交通设施无障碍设计要求

5.1 交通标志

5.1.1 字符

交通标志的字符信息应考虑视力等机能障碍者的出行方便性，合理设计其大小、间距、颜色以及亮度对比度等，具体要求如下：

a） 为方便视力障碍者辨识交通标志信息，应按照GB/T 31054-2014中4.2.1的规定采用提高颜色饱和度和对比度、加大字号和尺寸、缩短视距等方法设计文字和图形符号；

b） 为盲人设计的盲文提示牌应易于触摸和识别，盲文标志的表示方法应按照GB 50763-2012中3.16.2的规定采用国际通用的表示方法。

5.1.2 布局

交通标志应根据机能障碍者的出行便利性进行合理的布局，宜符合以下要求：

a） 宜根据无障碍人员的通行要求设置相应的无障碍交通标志；

示例：

换乘站出入口设置盲文提示牌，换乘连接处应设置无障碍标志告知换乘信息。

b） 无障碍交通标志应设置在行进方向最易于发现、辨识的位置，不应被栏杆、树和其他设施遮挡；

示例：

在坡道和梯道开始、结束和转弯地方使用无障碍提示标志；

c） 城市主要地段的道路和建筑物宜提供无障碍交通标志；

d） 宜根据行动障碍者、视力障碍者和听力障碍者的交通出行需求状况进行调研和科学预测，合理地布局无障碍交通标志的位置、数量和间距。

5.2 交通信号灯

交通信号灯的光色、持续时间和提示方式等应考虑机能障碍人群的特殊需求：

a） 交通信号灯宜配置便于出行的导向盲文铭牌及简单易懂的声音提示装置，提醒视力障碍人群穿过马路。声响设置应按照GB 14887-2011的5.12的规定；

示例：

采用国际通用的简单易识别的“鸟鸣”作为信号灯提示音。

b） 盲人过街声响提示装置宜考虑对周围居民的影响。如在城市白天环境噪声较高时，提示音量强度应适度提高，夜间则要降低，或在出行较少的深夜关闭；

c） 在机能障碍人群较多的地方，信号灯的持续时间宜综合考虑行动障碍者和视觉障碍者的安全通行时间。

5.3 人行道和人行横道

人行道和人行横道应考虑机能障碍者的通行需要，设置相应的无障碍辅助设施。人行道具体设计要求应按照GB 50763-2012中4.2规定，人行横道具体设计要求应按照GB 50763-2012中4.3规定。

5.4 人行天桥

人行天桥应考虑行动障碍者和视觉障碍者的通行需要，设置相应的无障碍辅助设施，人行天桥具体设计应按照GB 50763-2012中4.4和DB11/T 805-2011中3和4的规定。

5.5 停车场

停车场的无障碍设计要求如下：

a） 无障碍停车位的位置应紧挨无障碍出入口，有无障碍标志；

b） 无障碍停车位数量宜根据周边无障碍车位使用情况确定；

c） 停车场的无障碍出入口宜直接通向地面建筑内部或室外场地，与地面建筑的无障碍交通系统中的自动电梯、升降平台等相结合；

d） 对于存在高度差的无障碍停放设施，宜根据需要设置起伏较小的坡道、升降平台或电梯等辅助设施；

e） 停车场内的无障碍人行通道不宜跨越机动车道。

5.6 候车亭

候车亭应考虑如下无障碍设计要求：

a） 站台有效宽度应能方便轮椅通行；

b） 车道中间设置站台时，应考虑轮椅使用者的通行方便性；

c） 站台应设置盲道提示信息；

d） 应考虑候车亭盲道与人行道盲道的连接性；

e） 宜设置盲文站牌或语音提示服务设施，盲文站牌的位置、高度、形式与内容应方便视觉障碍者的使用。

GB/T XXXX -XXXX《城市公用交通设施无障碍设计指南》（报批稿）编制说明

一、 任务来源

本标准制定项目由中国标准化研究院根据国家科技支撑计划项目“城市公共基础设施宜人性关键技术及标准研究”的研究任务和研究目标提出，同时列入国家标准化管理委员会《2013 年制修订国家标准项目计划》，项目编号为20130247-T-469。本标准由全国人类工效学标准化技术委员会归口。本标准起草工作组由中国标准化研究院、北京航空航天大学、建设部标准定额所、北京市交通标准化技术委员会、交通部公路科学研究院等单位的专家组成。

二、 任务背景

城市公共基础设施指的是城市生存和发展所必备的基础设施中与人的生产活动息息相关的设施。之所以世界上不同的城市公共设施发展的情况存在很大的差异，是因为人类文明与城市的发展是伴随着社会经济的繁荣而发展起来的。发达国家因为工业化发展的起点早，工业化程度较高，有一定的经济实力投入建设城市公共基础设施。但由于不同国家、不同地区、不同民族的人，因地理位置、生活习惯、民族文化的不同，人的生理特征和心理需求存在较大的差异，例如，我国人体尺寸与欧美人体尺寸存在着很大的差异，欧美人相对于中国人来说，身材比较高大，如果按照欧美的设计要求来设计中国的城市公共基础设施，势必会影响中国人的使用体验和舒适感。选择符合人类工效学的舒适尺度是城市基础设施设计时必须考虑的，利用人类工效学技术标准来完善城市的使用功能，给人们出行活动创造便利，提升城市宜人性。因此，有必要借鉴国外丰富的建设城市公共基础设施的经验，根据中国人的生理心理需求以及使用习惯和偏好等，加强对中国城市公共基础设施宜人性的研究，提高我国城市公共基础设施的人性化设计水平，对于提升我国人民的公共体验和生活质量具有较大的意义和价值。

城市公用交通设施指的是由政府或其他社会组织提供的、给公众交通出行提供服务的城市中的公共建筑或设备用交通设施，包括交通标志、交通信号灯、反

光镜、减速带、人行道、人行天桥、停车场、计时收费器、候车亭、加油站和公路收费亭等。城市公用交通设施是与人民群众出行息息相关的基础设施，设施的宜人性建设直接影响着人们出行安全和方便，也是人文关怀的体现。为此，需要对城市公共交通设施的功能和特点进行研究，使城市公用交通设施的建设不仅符合国家相关质量标准，而且还能使人们的生活工作更为方便，从而提高人们出行生活的质量。

随着人们生活质量的提高和技术的发展，为弱势群体（如老年人、残疾人、伤病人、儿童等）提供方便、安全的城市公用交通设施已成为社会共识。目前，我国的城市公用交通设施的功能和交互形式越来越复杂，如何针对弱势群体设计方便、有效的城市公用交通设施已成为我国城市公用交通设施亟需解决的问题。因此，为了更好地为弱势群体营造安全、健康、舒适、高效的交通环境，有必要根据中国城市公用交通情况、中国弱势群体的特征和习惯偏好等对城市公用交通设施的无障碍设计进行要求和规定，为城市公用交通设施的无障碍设计和评价提供基本的参考和依据。

本标准是参考 GB 50763，GB14887，GB/T 10000，GB/T 10001.9，GB/T 12985，GB/T 13547，GB 5655，DB11/T 805 等标准，针对我国主要城市交通设施制定了无障碍设计指南。本标准给出了城市公用交通设施无障碍设计的一般要求，也可为城市公用交通设施无障碍评价和生产提供参考。

三、 工作情况

1. 标准起草组主要成员深入学习了国内外相关技术标准和文献资料，了解国内外相关技术标准现状和参考方法，明确了本项国家标准制定工作的重点，形成了 GB/T XXXX- XXXX《城市公共交通设施无障碍设计指南》初稿；
2. 标准起草组根据初步确定的标准初稿，开展了我国城市公共交通设施功能现状和使用现状调研（调研示例见图 1、图 2 和图 3），在对调研结果进行分析的基础上，依据我们城市公共交通设施的工效学现状以及我国人民的实际需求，确定标准的关键技术要素（工效学指标体系示例见表 1），形成了 GB/T XXXX- XXXX《城市公共交通设施无障碍设计指南》标准草案稿；

图 1 新加坡垂直电梯前盲道

图 2 新加坡各类出入口坡道

图 3 人行道斜坡设置不合理

表 1 停车场的无障碍设计指标体系

一级指标	二级指标	三级指标
停车场的无障碍	尺寸	坡道坡度
		无障碍停车位宽度
	布局	设置位置
		设置数量
	标识	文字
		标线
	照明	光强

3. 标准起草组在草案稿的基础上，广泛征求相关科研院所和设计应用部门的意见，同时结合标准中的主要技术要素，开展了实验研究和分析（研究示例见图 4），具体确定了标准中各技术要素的关键技术点和设计原则，形成了 GB/T XXXX- XXXX《城市公共交通设施无障碍设计指南》标准工作组讨论初稿；

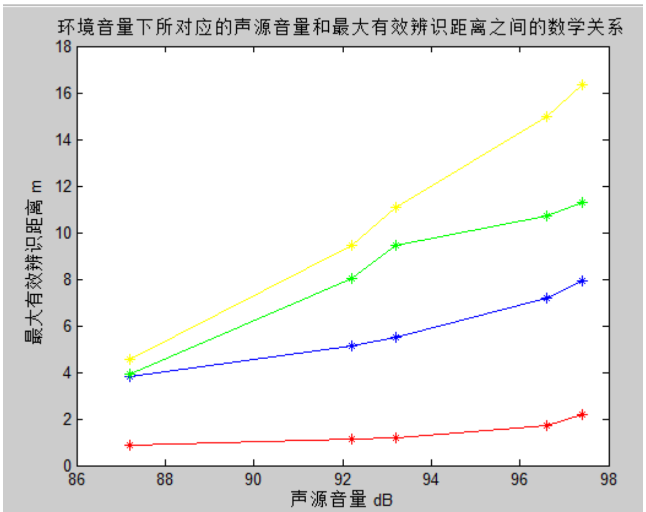

图 4 声源音量和最大有效距离数学关系图

4. 标准起草组就标准中相关技术要素和关键技术点的主要内容和设计原则进行了进一步的研讨和修改，形成了 GB/T XXXX- XXXX《城市公共交通设施无障碍设计指南》标准工作组讨论稿。
5. 标准起草组根据工作组讨论意见，对标准的相关技术内容进行了修改，同时为了更准确地反应标准的主要技术内容，根据专家建议，将标准的名字由“城市公共交通设施无障碍设计指南”改为“城市公用交通设施无障碍设计指南”。在征求了相关方的意见和建议基础上，形成了 GB/T XXXX- XXXX《城市公用交通设施无障碍设计指南》标准征求意见稿；
6. 标准主要起草组对收到的专家反馈意见进行了汇总，根据专家的意见和建议，在对标准原文再次进行认证推敲的基础上，对标准征求意见稿进行了全面、细致的修改，形成了 GB/T XXXX- XXXX《城市公用交通设施无障碍设计指南》送审稿。

四、 修订工作的原则

1. 按照GB/T 1.1- 2009 和GB/T 20000.2-2009的要求制定该项国家标准；
2. 标准名称由原来的“城市公共交通设施工效学无障碍设计指南”改为“城市公用交通设施无障碍设计指南”。

标准起草工作组

二零一四年十二月二十一日

GB/T ××××－×××× 《城市公用交通设施无障碍设计指南》

标准审查会会议纪要

2014 年 12 月 23 日，全国人类工效学标准化技术委员会（SAC/TC7）在北京召开了人类工效学国家标准审查会，此次会议到会的审查专家共有 25 名（名单见附件 1）。

审查会对国家标准《城市公用交通设施无障碍设计指南》（送审稿）进行了审查。会议由丁松涛委员主持。与会专家听取了标准起草组对标准编制情况的说明，对标准进行了逐条审查，形成了以下审查意见:

（1）该标准规定了城市公用交通设施无障碍设计原则，同时给出了主要公用交通设施无障碍设计要求，为我国城市公用交通设施的无障碍设计提供了重要的技术依据。

（2）该标准与现行国家法规、标准协调一致，编写格式符合GB/T 1.1－2009 的要求，对征求意见处理恰当。

（3）该标准是人类工效学基础标准，建议定为推荐性国家标准。

审查会一致通过了对该标准的审查，认为该标准达到国内先进水平。

审查会要求标准起草组按照审查会提出的主要审查意见（见附件 2）对标准文本进行修改后形成报批稿，上报国家质量监督检验检疫总局和国家标准化管理委员会。

审查组组长：丁松涛

2014 年 12 月 23 日